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Scallop Production Area 4 in the Bay of Fundy: Stock status and forecast

Zone de production du pétoncle 4 dans la baie de Fundy : état du stock et prévisions

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Abstract

Scallop landings in the Bay of Fundy from Scallop Production Area (SPA) 4 in 2000/2001 were 102 t (meats) against a total allowable catch of (TAC) of 110 t. As of 28 January 2002, 243 t had been landed against the current 2001/2002 TAC of 400 t. Fishing effort (hours) in the 2000/2001 season was the lowest in 26 years. Commercial catch rates to 7 January 2002 have averaged 47 kg/h in 2001/2002, compared to 16 kg/h in the previous season and are expected to increase by the current season's end. Since October 2001, average meat weights in the catch have decreased to 11 g. The average percentage of meats less than 8 g was at 7.4 percent as of the end of January 2002. The recommended upper limit for the percent of meats less than 8 g is 10 percent. The 2001 research vessel survey indicated that, due to the higher than average growth rate, the 1998 year-class was already recruiting to the fishery and had increased the biomass of commercial size scallops (shell height > 80 mm) in 2001 sooner than expected. The remaining portion of the abundant 1998 year-class will recruit to commercial size by the summer of 2002. Concerns about large increases in natural mortality as occurred in 1989/1990, are being addressed by a joint monitoring program conducted with industry. The population dynamics of this scallop population were modelled using a state-space form of the delay-difference model. A new model for the relationship between trends in the number of clappers (empty paired shells) and natural mortality was also included in the population model. Model parameters were estimated using Bayesian Gibbs sampling methods. Posterior distributions of projected biomass were used to evaluate in-season increases to the current TAC and potential future harvests against biomass reference points based upon a yield-per-recruit model.

Résumé

Les débarquements de pétoncle issus de la zone de production de pétoncles (ZPP) 4 en 2000–2001 se chiffraient à 102 t (chairs) d'un total autorisé des captures (TAC) de 110 t. Au 28 janvier 2002, 243 t du TAC actuel pour 2001–2002 de 400 t avaient été débarquées. L'effort de pêche (en heures) déployé pendant la saison 2000-2001 était le plus faible en 26 ans. Pour 2001–2002, le taux de prises commerciales au 7 janvier 2002 se situait en moyenne à 47 kg/h, en comparaison de 16 kg/h pendant la saison précédente. On s'attend à ce que ce taux augmente d'ici la fin de la saison en cours. Depuis octobre 2001, le poids moyen des chairs récoltées a diminué, atteignant 11 g. Le pourcentage moyen de chairs pesant moins de 8 g se situait à 7,4 % à la fin de janvier 2002, alors que la limite supérieure du pourcentage de chairs de ce poids se situe à 10 %. Le relevé de navire de recherche de 2001 a indiqué que, en raison du taux de croissance supérieur à la moyenne, la classe d'âge 1998 était déjà en voie d'être recrutée à la pêche, ce qui a donné lieu à une augmentation, plus tôt que prévu, de la biomasse de pétoncles de taille marchande (hauteur de la coquille > 80 mm) en 2001. Le reste de l'abondante classe d'âge 1998 sera recrutée à la pêche commerciale d'ici l'été 2002. Un programme de surveillance mené de concert avec l'industrie a été mis sur pied pour répondre aux préoccupations que soulève la forte augmentation de la mortalité naturelle, comme cela s'est produit en 1989–1990. Nous avons modélisé la dynamique de cette population de pétoncles en utilisant une forme d'espace d'états du modèle différentiel à argument retardé. Nous avons aussi inclus dans le modèle de la population un nouveau modèle de la relation entre les tendances dans le nombre de coquilles vides et la mortalité naturelle. Nous avons utilisé les

méthodes d'échantillonnage Bayes-Gibbs pour estimer les paramètres du modèle et les distributions à posteriori de la biomasse prévue pour évaluer les augmentations en saison du TAC actuel et des récoltes futures potentielles par rapport à points de référence de la biomasse reposant sur un modèle du rendement par recrue.

Introduction

In the 2000 assessment of Scallop Production Area (SPA) 4, Smith and Lundy (2000) used the modified DeLury model (Collie and Sissenwine 1983, Conser 1995) to characterize the population dynamics for the years 1991 to 2000. Over this period there had been a general decline in abundance as measured by survey indices and commercial catch rate. This kind of trend is referred to as a "one-way trip" by Hilborn and Walters (1992) and models fit to these kind of data generally get the trend right but estimates of absolute population size or biomass could be biased.

Over the last year we have recovered survey and commercial fishery data from prior to 1991. These data are now loaded into our database and will be used in this assessment. In the late 1980's, two very strong year-classes (1984 and 1985) recruited to the fishery but were decimated by a combination of large catches and catastrophic natural mortality. Trends in mortality will be difficult to estimate within the modified DeLury model. Moreover, preliminary results from an analysis of selectivity of scallops to the dredge survey data indicate that catchability coefficients for fully-recruited and recruit scallops are not equal — opposite to what has been assumed in previous assessments. Only one of these catchability coefficients can be estimated in the DeLury model with the other assumed to be related in a deterministic way. The selectivity analysis has not advanced far enough to provide an independent estimate of the relationship between the two coefficients.

This year we have used a form of biomass dynamic model, the delay difference model, for the population dynamics. This new model is similar to the Delury model in that it uses survey estimates to characterize the population. The advantages of using this model are that catchability coefficients for recruits and fully-recruited scallops can both be estimated. In addition, natural mortality was also estimated using the clapper (dead paired shells) information from the surveys. The parameters of this model are estimated using Bayesian methods which provide a basis for incorporating uncertainty into parameter estimates and into evaluating management actions.

The fishing season in SPA 4 has been changed to start 1 October and end 30 April the following year. Currently the fishery is operating under a 400 t TAC for the 2001/2002 season with restrictions on shell heights and meat weights. In this document we evaluate potential in-season increases to this TAC as well as possible harvest levels for 1 October 2002. The 1998 year-class continues to look very strong and will be the mainstay of this fishery in the near future.

There are no objectives and associated reference points for this fishery. Some potential candidates are presented in this paper, but discussions between the fishing industry and DFO to develop objectives for the scallop fisheries in the Bay of Fundy are required.

Fisheries data

Landings

On 1 January 1997, an area-based management plan was implemented for the scallop fishery in the Bay of Fundy dividing the Bay into 7 Scallop Production Areas (SPAs). In 1999, SPA 3 and 7 were combined reducing the number of SPAs to 6 (Fig. 1). Landings have only been reported by SPA since 1997. In this report, we present for the first time a reconstruction of landings for SPA 4 from 1976 to 1996 (Table 1).

The landings prior to 1997 were reconstructed from a number of landings data sources and commercial logbooks. For the period from 1976 to 1996, scallop landings were reported by NAFO unit area and vessel size. Landings by vessels > 25.5 GT and < 19.8 m LOA from NAFO subareas 4XRS (Bay of Fundy and approaches), 4XQ (Lurcher Shoal/German Bank) and 4Xu were used to represent those of vessels now categorized as the Full Bay fleet. Landings reported as 4Xu indicate those landings for which location beyond the NAFO unit area was unknown. These landings were apportioned to 4XRS and 4XQ using the proportion of catches recorded in the fishing logs for these latter two areas. Commercial logs were also used to apportion catches in 4XRS to the Bay of Fundy and the current Brier Island area of SPA 3 and St. Mary's Bay.

Scallop landings were reported by licence type from 1985 to 1996 and landings of vessels by the Bay of Fundy fleet licences were assumed to be consistent with those by vessels now identified as Full Bay Fleet. Landings were not recorded by area in these records and include those from German, Browns and Georges Bank, as well as from the Bay of Fundy and approaches. Landings by vessel size and NAFO subarea were used to identify those from Georges and Brown's Bank. Log books were used to apportion landings between what is now SPA 3 and German Bank.

Over the entire period of 1976 to 1995, landings by the Full Bay Fleet were apportioned between SPA 1 and 4 using the portion of landings identified being in either area in the log books. In 1996, landings from log records for the limited opening in fall for the Inside Zone (less than 6 miles from the Nova Scotia coast) in Digby grounds were accepted as being accurate and the log books were only used to apportion between SPA 1 and 4 for the remainder of year.

For much of the history the fishery in what is now SPA 4, the fishing season in the Inside Zone was from October to May. Landings in the remaining portion of SPA 4 could occur year-round. The landings by fishing season from 1976/1977 to 1995/1996 in Table 2 were defined as being from 1 October in year t to 30 September in year $t + 1$. From 1997 to 2000, the season was restricted from October to December except for 1998 when the season began in September. In 2000/2001, the season was extended to the spring again and landings continued to be reported from the SPA until August of 2001. The season in 2001/2002 has been defined to be from 1 October to 30 April.

The complete landings for SPA 4 as described above are presented in Fig. 2. The series starts in 1976 when logbooks with requirements for location data were introduced. Landings are available from before 1976 but locations with respect to SPA were unknown. Landings for Bay of Fundy prior to 1976 have been reported in Caddy (1979) and Black et al. (1993).

The major trends in the landings series are the decline from 1980 until the large increase in 1987/1988 and 1988/1989 due to the very abundant 1984 and 1985 year classes. Catastrophic natural mortality occurred during spring 1989 through to 1990 and landings declined through this period. Thereafter, landings declined or remained low. Total allowable catch (TAC) regulation was introduced for the 1997/1998 season and the levels that were set are given in Table 2 and Fig. 2. The TAC and landings have increased in the 2001/2002 season due to the very stong 1998 year-class (see Survey data section).

An interim TAC of 300 t was set for the opening of the 2001/2002 fishery and then raised to 400 t in late December 2001 by fisheries management in consultation with Science. Initially, fishing activity in 2001/2002 was restricted to the Digby Gut to Parkers Cove area to protect the 1998 year-class (Fig.3). While this year-class is fairly wide-spread in its distribution (See Survey section), concentrations appeared to be highest in Digby Gut to Gullivers Head area. After 30 October, the whole area was open for fishing.

New conditions of a minimum meat weight of 8 g and minimum shell height of 76 mm were introduced for the 2001/2002 season. The 8 g limit was monitored using meat weight samples of the catches with a tolerance of allowing for samples to have no more than 10 percent of the meats by number less than 8 g. The previous conditions of a meat count of 45 per 500 g and minimum shell height of 95 mm caused some confusion as one could have a meat sample that had a legal count but come from scallops with shell heights less than 95 mm.

Catch and effort

Catch rate and effort were calculated from log books in which all of catch, effort and location (class 1 data) were recorded (Table 2). The proportion of catch represented by the logs has been variable over time with the lowest (around 10 percent) occurring during the peak landing years of the late 1980's.

During the early 1980's catch rates declined but landings were maintained by increasing effort (Fig. 4). Increased landings in 1987/1988–1988/1989 reflect increases in catch rate and effort as the very strong 1984 and 1985 year-classes recruited to the fishery. Catch rate declined throughout the 1990's and landings were maintained by high effort until the closure of the Inside Zone in 1995 and the limited fall opening in 1996. Increased catch rates in 2001/2002 reflect early recruitment of the fast growing 1998 year-class.

The catch rates in Fig. 4 were estimated as the sum of catch divided by the sum of effort for class 1 data from the commercial logs. These estimates may not adequately represent the true catch rate during years when the reporting rate for log books was poor. Using the available data by month in those years to estimate annual catch rates may result in biased estimates because of seasonal trends in meat weights.

Another approach to estimate catch rate is to fit a linear model to the catch rate by month data over all years and predict a standardized catch rate for the same month each year (Gavaris 1980). This model assumes that catch rates by month exhibit the same relative relationship with each other for all years. Differences between years are simply due to an overall annual effect.

This kind of model fits the monthly catch rate well (Table 3) and predicted that catch rates in October were on average higher than for the other months. Overall, the predicted catch rate for October each year differed little from the annual estimate except for the first five or so years of the series (Fig. 5). For much of the series the actual catch rates for October were as high or higher than for the rest of the months except for the period 1976 to 1981.

Sampling of catches

We have completed the construction of a database for samples of the meat weight composition of the commercial catches. This database now has data from 1983 through to the present. Prior to 2000, samples were collected on a voluntary basis from fishermen and costs were covered by the department. Since 2000, samples have been collected through the dockside monitoring program.

The meat weight data from 1983 to the end of the 2000/2001 fishing season are summarized in Table 4. Note the tendency for very small meats being taken in the commercial catch in the earlier years. A comparison of the monthly meat weight averages in Table 5 with the monthly distribution of catch in Table 1 shows that sampling was quite sparse with respect to the main fishing season in the Inside Zone in the years prior to 1992/1993.

The 2001/2002 data for meat weights are presented separately in Table 6 with added information on the proportion of the number of meats that weighed less than 8 g. Note that the meat weight has been decreasing each month during the current season and the mean percent of the number of meats less than 8 g is approaching the 10 percent threshold set for this fishery. Locations associated with the meat weight samples are mapped in Fig. 6.

Survey data

Dredge surveys have been conducted in the area since 1981. These surveys have been conducted every June but vessels, gear and the stratification schemes have changed over time. From 1981 to 1988, the survey was conducted on board a commercial scallop vessel using 7-gang gear. Since 1989, the government vessel **J. L. Hart** has been used with 4-gang gear but estimates have been expressed in terms of 7-gang gear throughout the whole time series. The only change that has been made to the dredge design was the introduction of rubber washers in 1983.

Each year, two (three when 7-gang gear used) of the survey dredges were lined with 38 mm polypropylene stretch mesh. Catches in the lined gear were used to estimate the abundance of scallops with shell height less than 80 mm while the catches from the unlined gear were used to estimate the abundance of scallops with shell heights greater than or equal to 80 mm. Catches of scallops with shell heights less than 40 mm are thought to give qualitative indications of abundance only due to uncertainties about catchability of the small animals.

In surveys from 1981 to 1990, stations were allocated to strata defined to encompass areas of similar commercial effort (low, medium and high) in the recent fishery, based on log book information. Strata were defined to be fixed areas in 1991 and these boundaries have remained the same since then (Fig. 7). The distribution of stations indicates that the area covered by the survey has remained fairly constant since at least 1982 although the sample size has increased with time (Fig. 8a–d). In this assessment we have assumed that the survey estimates are consistent for population abundance throughout the whole series despite the differences in design and vessel.

The mean numbers per tow and standard errors for three size groups (> 80 mm, 40–79 mm and < 40 mm) in each of the strata in SPA 4 from the 2001 survey are presented in Table 7. At the bottom of the table, the stratified mean and its standard error are given for all of the strata as well as for areas within two depth ranges. These ranges were identified as being important for differences in the growth rates of the scallops (Smith and Lundy 2000, Smith et al. 2001). Note that for the scallops less than 80 mm, the mean densities are higher in the deeper water areas but overall abundance is lower than for the shallower areas due to the smaller area associated with the deeper water. Therefore, survey abundance indices are calculated as total numbers for depths less than 90 m and deeper, separately and then summed together.

Size composition and growth

The shell height frequencies for the entire survey series are presented in Figs 9a–c. While the population appears to be going through a recruitment event in 2000–2001 similar to that of the mid-1980's, the particular point to note is the apparent accelerated growth rate exhibited by the strong year-class 1998 year-class first detected in the 2000 survey. This year-class had a broad

mode of 37.5 to 47.5 mm at age 2 and then peaked at around 77.5 mm at age 3 in 2001. If this rate continues the year-class will be fully recruited before it is four years old.

Starting in October 2000, we initiated a series of monitoring surveys with a commercial scallop vessel (F.V. Julie Ann Joan, Captain Kevin Ross) to observe clapper rates between our regular June surveys. These surveys cover the same strata every two to three months. We have also used these surveys to track the growth of the 1998 and other year-classes in the fishery. These data indicate that age 2 scallops had an average shell height of 45.6 mm in June 2000 but had grown to 74.4 mm at age 3 in May 2001 (Table 8), far larger than the 65.1 mm expected for June based on the relationship in Fig. 10. The data in this figure were from the 1996 survey which is the only year we have ages for all of the shells collected. The 1993 to 1997 year-classes also exhibited higher than expected growth rates in 2001. Note the continued high growth rate exhibited by the 1998 year-class scallops from June to November of 2001 compared to similar age scallops from the 1997 year-class in 2000.

There is anecdotal information that strong year-classes tend to grow faster than weak year-classes. The only additional age data that we can bring to bear on this hypothesis is the data set analysed in Smith et al. (2001). These data consist of shell heights for each age ring on the shells of 706 scallops caught during the June 1990 survey. The average shell height at age for the 5 main year-classes in the sample are presented in Table 9. The 1983 year-class was believed to be a relatively weak year-class and appears to have had a slower growth rate than the extremely strong year-classes that followed. While these data are very limited, it appears from Figs 9a–c and Table 8, the 1998 year-class has been exhibiting record high growths relative to other year-classes strong or otherwise, in the 21 year history of the survey.

This trend of a higher growth rate for scallops in 2001 is also evident in the the meat weight-at-age data collected during the monitoring surveys (Table 10). The expected meat weights were predicted from the fit of the 1996 meat weight-at-age data for depths less than 90 m presented in Fig. 11. Note the lack of increase in meat weight with age for scallops in the deeper water of SPA 4 after age 13.

The average meat weight-at-shell height for the 2001 survey was also higher than that observed for the 2000 survey and was somewhat higher than observed for the 1999 survey (Table 11). In 1999, meat weight-at-shell heights had been the highest observed since 1996 in SPA 4 and were also noted to be very high for offshore scallops (Robert et al. 2000).

The seasonal changes in meat weight-at-shell height are presented in Table 12. Again, the pattern of faster growth rate for 2001 is evident here. Scallops with shell heights of 85 mm and larger will be recruited to the fishery given the new 8 g meat weight limit. A proportion of the animals with shell heights between 80 and 85 mm will also have meats large enough to be harvested in the 2001/2002 season.

Population components

In past assessments, the components of the scallop population identified as being fully-recruited (or commercial size) or expected to recruit to the fishery in a year were defined by shell height size ranges. Fully-recruited animals were assumed to have shell heights of 80 mm and greater until 1997 when a minimum shell size of 95 mm was introduced. However, the minimum meat weights observed from commercial samples from 1997 to the present (Table 4) seems to indicate that the 95 mm limit was probably not adhered to. In addition, meat weight samples from prior to 1996 show

that some animals as small as 60 to 70 mm were being retained in the catch. The regulations for the fishery have also been changed in 2001 to a minimum shell height of 76 mm with a minimum meat weight of 8 gm. Thus, we will define fully-recruited scallops to be any animals with shell height of 80 mm and larger for the whole series. The 80 mm limit should correspond to scallops with 8 gm and larger meat weights allowing for the current 10 percent threshold on smaller meats (Table 12). The time trend for the fully recruited portion of the survey using this definition is presented in Fig. 12.

The definition of recruitment depends on the size ranges of scallops that will grow to be 80 mm and larger in the following year. The shell height-at-age relationship in Fig. 10 suggests that a 60 mm scallop in June of one year would grow to 80 mm by the June of the next year. For most years then, recruitment would be estimated from the survey based upon all scallops with shell heights between 60 and 80 mm in the June survey. The frequency plots in Fig. 9c indicates that a substantial portion of the 1998 year-class grew to be larger than 80 mm by June 2001. The increase from 45.63 in June 2000 to 74.36 in May 2001 for the 1998 year-class in Table 10 implies an annual rate of increase of 1.094. Assuming the model in Fig. 10 still applies, then scallops with shell heights of at least 47 mm would have grown to be 80 mm by June 2001. Shell height frequencies for the survey are only available in 5 mm bins and therefore we have defined the recruitment index from the 2000 survey as including all scallops with shell height between 45 and 80 mm.

The 60 to 80 mm range would capture the remainder of the 1998 year class for the recruitment index from the 2001 survey. The 1999 year-class appears to be larger at age 2 than the 1998 year-class was at the same age and is probably mixed in with the peak that we have been identifying as the 1998 year-class in Fig. 9c. The time trend for the recruitment index defined above is presented for the year it was observed in Fig. 12.

The spatial distribution of pre-recruits (shell height less than 45 mm), recruits (shell height between 45 and 80 mm) and fully-recruited (shell height greater than 80 mm) in the 2001 survey are presented in Figs 13 to 15, respectively. The pre-recruits are probably 1999 year-class scallops and appear to have a more limited distribution than the 1998 year-class with the higher density areas being generally in SPA 1. The recruits (1998 year-class) are spread out from about 4 to 12 miles from the Nova Scotia coast and from Delaps Cove to Gullivers Head. The fully-recruited scallops are less widely distributed than the recruits with the higher densities in the Digby Gut and Delaps Cove strata.

Survey Biomass

The regular collection of shell height, meat weight and shells for ageing from the June surveys has only been conducted since 1996. While a biomass index could be estimated for the 1996–2001 surveys, some form of average meat weight shell height relationship would need to be used to estimate biomass for the years previous to 1996. Smith and Lundy (2000) analysed the meat weight (w_i)/shell height (H_i) relationships for each year from 1996 to 2000 and demonstrated that a relationship that included a piecewise relationship with depth of the following form provided an adequate fit.

$$\log(w_i) = log(\alpha) + \beta_1 \log(H_i) + \beta_2 \log(\text{depth}|\text{depth} > 90), \quad (1)$$

where,

$$(\text{depth}|\text{depth} > 90) = \begin{cases} \text{depth} & \text{if depth} > 90 \\ 0 & \text{otherwise.} \end{cases}$$

We have updated this analysis here by including data from 1996 to 2001 in the analysis and tested for the differences between years[1] (Table 13). This analysis indicates that the relationship between meat weight and shell height in 1996 and 1999 were not significantly different. All other years exhibited significant differences from 1996 with the two most recent years having larger meats at shell height in the series.

Given the variation exhibited over the six years, the best available estimate of meat weight-at-shell height for the earlier years is probably the average predicted values from the models in Table 13. However, this would ignore the depth effects which are significant in all years. Instead, we used a reduced model which ignored differences between years to predict meat weight caught based on shell height and depth for each tow for all surveys from 1981 to 1995. The resultant biomass series for recruits and fully-recruited scallops as defined earlier are presented in Fig. 16.

Natural Mortality trends

The number of clappers or paired empty shells caught by the survey gear are also recorded each year. The stratified total number of clappers for fully-recruited scallops shows that for most years, numbers of clappers are relatively low, except for the very sudden increase in 1989–1990 corresponding to the catastrophic mortality that occurred during those years (Fig. 17).

Estimates of the instantaneous rate of natural mortality, M, have been calculated from clappers by Dickie (1955) and Merrill and Posgay (1964) using the formula,

$$a = 1 - \exp(-(Z/(D/365))(1/L)). \tag{2}$$

where a is the annual rate of natural mortality, Z is the mean number of clappers in the survey, D is the average time in days required for the shells to separate and L is the mean number of live scallops in the survey. The exponent of equation 2 was assumed to be equal to M such that,

$$M = (Z/L) \times D/365. \tag{3}$$

Dickie (1955) used results from tank experiments to estimate D to be on average 50 days for scallops with shell heights less than 96 mm and 100 days for shell heights between 96 and 155 mm in his analysis of mortality rates for the Digby area. On the other hand, Merrill and Posgay (1964) determined that based on the general condition of the ligament, the shell, the kinds and degree of fouling on the shell and the position of the latest ring with respect to the shell edge of clappers caught on Georges Bank, the average time that clappers persisted was 231 days.

Clappers are created when a scallop dies and the shells remain attached and *die* when the hinge dissolves. The estimate in equation 3 requires that the birth rate of clappers ML equals its death rate, $(D/365)Z$, i.e., the population of clappers is in equilibrium. Given the rapid increases in the population due to the 1984 and 1985 year-classes and the catastrophic mortality that followed, the assumption of equilibrium is not valid here.

[1]Note: Depths have yet to be corrected for tides.

Alternatively, we could assume that clappers have a fixed *lifespan* and the processes that cause dissolution are such that the hinges of clappers of the same age come apart in a narrow time interval — much like popcorn kernels exploding within a short time once the right temperature of the cooking oil has been reached. The details of this so-called Popcorn model[2] are presented in the Appendix where the number of clappers at time t is approximated as,

$$Z_t = M_t \int_{t-S}^{t} \left[(t-\tau) L_{t-1} + (1-t+\tau) L_t \right] d\tau \tag{4}$$

where $S = D/365$ is the separation time of a clapper. Completing the integration and solving for M gives,

$$M_t = \frac{2Z_t}{S\left(SL_{t-1} + (2-S)\,L_t\right)} \tag{5}$$

Note that under equilibrium ($L_{t-1} = L_t$), this equation reduces to equation 3. Even when not in equilibrium, the quantity $\frac{1}{2}[SL_{t-1} + (2-S)L_t]$ can still be regarded as a weighted average of the population between time $t-1$ and t. Thus, the clapper ratio can still be regarded as proportional to natural mortality, provided that the number of live animals employed in the ratio is not the present instantaneous abundance, but some average of present and past abundances.

Estimates of M from equations 3 and 5 for an arbitrary separation time of 231 days are presented in Fig. 17. The survey estimate of clappers is indexed by the year of the survey but the mortality estimates derived from them are assumed to reflect mortality in the previous fishing season. The two kinds of mortality estimates exhibit the same general trend but the non-equilibrium form dampens the effect of the rapid changes in the live population.

Selectivity analysis

In past reports for this and the other SPA's, the survey estimates of fully-recruited scallops and recruits were assumed to be on the same scale. That is, the catching efficiency of the survey gear was independent of the size of the scallop as long as the numbers of scallops less than 80 mm were estimated from the lined dredges and the larger scallops were estimated from the unlined dredges only. This was an important assumption used in the population model in Smith and Lundy (2000).

Shell height frequencies are available from both the lined and unlined gear from the surveys in the data base and the assumption of equal fishing efficiency can be tested. A preliminary investigation was conducted for the combined frequencies of scallops caught in the lined and unlined gear from the surveys for 1997 to 2000. The conditional probability that a scallop of shell height (h) was retained in the unlined gear given that it entered the path of the gear was modelled using a logistic curve for the selection-at-height.

$$\phi(h) = \frac{p \exp(a+bh)}{(1-p) + \exp(a+bh)} \tag{6}$$

The a and b terms are parameters for the logistic model and p represents the fishing efficiency relative to the lined gear. When $p = 0.5$, then the scallop is equally likely to be retained by either the lined or unlined gear. The lined gear was assumed to retain all scallops that entered it.

[2]The Popcorn model was suggested by R. K. Mohn and formulated by D. Hart.

This model was fit to the data using the SELECT method of Millar (1992). The logistic model was a reasonable fit to the data (Fig. 18). The main interest here is in the estimates for p which range from 0.57 to 0.61 over the four years. We interpret this to mean that for shell heights greater than approximately 80 mm which should not pass through either gear, 57 to 61 percent of these scallops encountered were retained in the unlined gear compared to 39 to 43 percent for the lined gear. If this fishing efficiency extends over all sizes then the catch of the lined gear from 40 to 80 mm would need to be multiplied by approximately 1.43 (59/41) to be on the same scale as the catch from the unlined gear.

Combining frequencies from all tows in a survey will tend to mask tow-to-tow variation and possible effects due to bottom type on the performance of the dredge (Robert and Lundy 1988). Analysis of the individual tows is not straightforward but an initial attempt was made by applying the random effects model of Fryer (1991) to a subset of individual tows from the 2000 survey. Results from these tows indicated an estimate of 0.57 for p with 95 percent confidence limits of 0.52 and 0.63 (Pers. comm. R. Fryer, SOAFD). Hence, even when the data are analysed at the individual tow level, the unlined gear has a significantly higher retention rate than the lined gear.

Population Models

In Smith and Lundy (2000), we used the modified DeLury or CSA model (Catch-Survey Analysis, Collie and Kruse 1998) to reconstruct the dynamics of the SPA 4 scallops over the 1991 to 2000 time period. This model was based on the numbers of scallops caught in the surveys and the estimated numbers caught in the fishery. The population declined throughout this period. Fitting populations to a declining (or increasing) trend only usually results a good fit to the trend but a poor estimate of population abundance — the so-called one-way trip problem (Hilborn and Walters 1992). Compare the estimates of population numbers in the columns labelled 'This Year' and '1991–2001' in Table 19. The addition of one more year of data (2001) changes the estimates of population numbers even though the structure of the model was the same for the two series. Our definition of what constitutes a fully-recruited scallop has changed from that used in Smith and Lundy (2000) where fully recruited for the period after 1996 were assumed to be scallops with shell heights greater than 95 mm. This change is responsible for the difference between estimates in the columns labelled 'Last Year' and 'This Year' in the table.

Applying the CSA model to the 1981 to 2001 time series (Table 14) should get around this problem but we have other issues that need to be addressed. The catchability of the fully-recruited scallops and recruits in the survey was assumed to be equal for the CSA model. The results of the selectivity analysis suggest that the equal catchability assumption is not tenable. Catchabilities for these two size categories can not be estimated separately in the CSA model and the selectivity analysis is not sufficiently advanced enough to provide estimates of the relationship between the two.

Natural mortality was assumed to be constant and known in the CSA model used in Smith and Lundy (2000). While the model can be formulated such that natural mortality can vary over time, these mortalities can not be easily estimated within the model. Natural mortality is a non-linear parameter in the model and the Kalman-filter approach used to estimate the parameters has difficulty with nonlinearities (Carlin et al. 1992).

The importance of having reliable estimates for catchability and mortality can be seen in the differences between the estimates of population numbers in the three rightmost columns of Table 19. Population estimates for any one year can vary by half or double depending upon the structure assumed in the model for these parameters.

Finally, the estimate of numbers of scallops in the catch had been obtained using estimates of average meat weight from commercial samples. As we have already noted, the number of samples and the seasonal coverage have varied over time especially in the period prior to 1992/1993. Our estimates of average meat weight from the survey are either directly estimated or predicted from the average shell height in the survey. Comparing these estimates with those from the commercial sampling program raises questions about the reliability of the latter estimates especially during the 1990's (Fig. 19).

Biomass dynamic models

The alternative to modelling changes in population numbers is to use catch weight and model changes in population biomass over time t.

$$(\text{Adult Biomass})_{t+1} = (\text{Surviving Adult Biomass})_t + (\text{Recruitment Biomass})_{t+1} \tag{7}$$

where,

$$\begin{aligned}(\text{Surviving Adult Biomass})_t \;=\; & (\text{Adult Biomass})_t + (\text{Biomass increase due to growth})_t \\ & - (\text{Losses due to Natural Mortality})_t - \text{Catch}_t\end{aligned}$$

Adult biomass is synonymous with the biomass of fully-recruited scallops in our case. We can write the above in a more compact form,

$$B_{t+1} = B_t + G(B_t) - M(B_t) - C_t + R_{t+1} \tag{8}$$

The simplest form of this kind of model is the surplus production model in which growth, recruitment and mortality are all contained in one term.

$$B_{t+1} = B_t + g(B_t) - C_t \tag{9}$$

where B_t and C_t are the population biomass and the commercial catch in year t. The term $g(B_t)$ corresponds to the increases due to growth and recruitment and the losses due to natural mortality. One common form for $g()$ is the following due to Schaefer (1954).

$$g(B_t) = rB_t\left(1 - \frac{B_t}{K}\right) \tag{10}$$

In this equation r corresponds to the intrinsic growth rate. The carrying capacity or the level of stock biomass corresponding to equilibrium conditions, that is, growth balanced by mortality, is represented as K. For the equilibrium form of the model, K is assumed to be the stock biomass before fishing started on the stock.

Scallop populations in the Bay of Fundy have exhibited episodic recruitment and mortality events (Dickie and Medcof 1963, Medcof and Bourne 1964, Kenchington et al. 1995). The surplus

production model assumes that r is constant over time and therefore events such as large recruitment events would have to be balanced out by decreases in growth or increases in mortality or both. The basic data used to fit this kind of model are time series for catches and catch rates (or effort series) and these kind of data do not contain information on growth, recruitment or mortality.

A more realistic approach is to model the terms in equation 8 individually.

Deriso (1980) developed such an approach by first defining the total stock biomass for recruited animals at the beginning of year t, B_t as,

$$B_t = \left[\sum_{a=k+1}^{\infty} N_{a,t} w_a \right] + w_k R_t, \tag{11}$$

where,

$N_{a,t}$ = Population numbers of fully recruited scallops age a ($a = k+, k+1, \ldots$) in year t.
R_t = Population numbers of scallops that recruit in year t (at age $a = k$).
w_a = weight at age a.

Next, Deriso (1980) makes three assumptions about the growth, survival and harvesting for the population. With respect to growth, he assumed that the increase in mean body size with age can be modelled as,

$$w_a = \alpha + \rho w_{a-1}, \tag{12}$$

where w_a is as defined above and α and ρ are unknown parameters. Secondly, selection to the fishery is assumed to be "knife edge" for all ages k and older. Finally, the rate of natural mortality rate is the same for all animals recruited to the fishery.

Total survival rate is assumed to be the product of natural survival rate and survival through harvesting.

$$s_t = s_t^M s_t^F \tag{13}$$

Writing $N_{a,t} = s_{t-1} N_{a-1,t-1}$ and $w_a = \alpha + \rho w_{a-1}$ in equation 8 and factoring out the terms that do not depend on age (e.g., s_t, α) results in sums over ages k and older for year $t-1$ in terms of total biomass,

$$B_t = s_{t-1} \alpha N_t + s_{t-1} \rho B_{t-1} + w_k R_t \tag{14}$$

and total numbers

$$N_t = s_t N_{t-1} + R_t. \tag{15}$$

After more algebra and noting that $\alpha = w_k - \rho w_{k-1}$ these two equations can be combined to give the form of the delay-difference model suggested by Schnute (1985).

$$B_t = s_{t-1} B_{t-1} + (\rho s_{t-1} B_{t-1} - \rho s_{t-1} s_{t-2} B_{t-2} - s_{t-1} \rho w_{k-1} R_{t-1}) + w_k R_t. \tag{16}$$

The first and last terms in the model define biomass in the current year as being a function of surviving biomass from last year and biomass of new recruits added to the stock this year, respectively. The middle term in brackets represents the growth of surviving individuals from last

year. This term can be greatly simplified if the average weight of the scallops ages $k+1$ and older, $\bar{w}_t$ is known. Substituting $N_{t-1} = B_{t-1}/\bar{w}_{t-1}$ into equation 15 results in (Hilborn and Walters 1992),

$$B_t = s_{t-1}\left(\rho + \frac{\alpha}{\bar{w}_{t-1}}\right) B_{t-1} + w_k R_t. \tag{17}$$

Note that the growth factor $\rho + \alpha/\bar{w}_{t-1}$ will decrease (increase) as the average size increases (decreases) representing an older slower growing (younger, faster growing) population. We use this form of the model with α and ρ given by the regression estimates on Fig. 11.

Estimation

The major impediment to using the delay-difference model has been the difficulty in estimating the parameters of the model. Deriso (1980) proposed a regression approach to estimate some of the parameters but could not estimate the states B_t. Hilborn and Walters (1992) present some state-space approaches that could only estimate the parameters assuming that either the process error or observation error were known but not both.

Quinn and Deriso (1999) and Meyer and Millar (1999) recommended that a Bayesian approach to estimation could get around the problems of the intrinsic non-linearity of the model, the time series nature of the problem and the inclusion of both measurement and process errors. Both groups of authors recommended similar approaches and we will follow that of Meyer and Millar (1999) here. In their exposition, fishing was assumed to occur at the beginning of the year, that is,

$$s_t^F = \frac{B_t - C_t}{B_t}, \tag{18}$$

where C_t is commercial catch as defined above. The stochastic form of the model in equation 17 is expressed as follows.

$$B_t = \left(\exp\left(-M_{t-1}\right)\left(\rho + \frac{\alpha}{\bar{w}_{t-1}}\right)\left(B_{t-1} - C_{t-1}\right) + w_k R_t\right)\mu_t. \tag{19}$$

Estimates for ρ, α, $\bar{w}_t$ and w_k are estimated outside of the model from growth data. Proxies for B_t, M_t and R_t are obtained from survey biomass index for fully-recruited scallops, survey clapper ratios and survey estimates of recruits in the following observation models.

First we assume that there is a proportional relationship between the survey biomass I_t and the population biomass.

$$I_t = q_I B_t \varepsilon_t \tag{20}$$

The survey recruitment index R_t' is used for the biomass of recruits.

$$R_t' = q_R R_t \nu_t \tag{21}$$

Finally, we used the Popcorn model for natural mortality as

$$Z_t = \frac{S}{2} M_t \left[S L_{t-1} + (2 - S) L_t\right] \epsilon_t. \tag{22}$$

The observation model for the number of live scallops from the survey was modelled as,

$$L_t = q_I B_t / w_t \varphi_t \tag{23}$$

We assume that all of the error terms given above (i.e., μ_t, ε_t, ν_t, ϵ_t and φ_t) are independent log normal random variates with unknown means and unknown variances σ^2, σ_ε^2, σ_ν^2, σ_ϵ^2 and σ_φ^2, respectively. The means will be derived from the expected values of equations 20–23.

The parameters to be estimated are the variance terms given above, the proportionality constants q_I and q_R and the dissolution rate S, as well as the state variables B_t, R_t and M_t for all t in equation 19.

In the Bayesian approach, one proceeds by defining the probability distribution (or likelihood function) for the observations y, that is, the observations in equations 20–23. Here catches are assumed to be known constants, referred to as control variables in state-space models, although models with catch as random variables can be constructed.

$$p(\mathbf{y}|\boldsymbol{\theta}) = \prod_{t=1}^{n} f_1(I_t|\boldsymbol{\theta}) \prod_{t=1}^{n} f_2(R_t'|\boldsymbol{\theta}) \prod_{t=1}^{n} f_3(C_t|\boldsymbol{\theta}) \prod_{t=1}^{n} f_4(L_t|\boldsymbol{\theta}) \tag{24}$$

The parameter set $\boldsymbol{\theta}$ refers to all of the unknown parameters given above, except for the variance terms. Further we suppose that these unknown parameters are random quantities with *prior* distributions $\pi(\boldsymbol{\theta}|\boldsymbol{\eta})$, where $\boldsymbol{\eta}$ is a vector of the variance terms, generally referred to as hyperparameters (Carlin and Louis 1996) in our model. The prior distributions reflect our view of the state of nature prior to collecting the data. Having collected these data, we update our view of the state of nature and express this update as *posterior* distributions.

$$\mathbf{p}(\boldsymbol{\theta}|\mathbf{y}, \boldsymbol{\eta}) = \frac{p(\mathbf{y}|\boldsymbol{\theta})\,\pi(\boldsymbol{\theta}|\boldsymbol{\eta})}{\int p(\mathbf{y}|\mathbf{u})\,\pi(\mathbf{u}|\boldsymbol{\eta})d\mathbf{u}} \tag{25}$$

Summaries of our updated knowledge about the elements of $\boldsymbol{\theta}$ such as means, medians, etc., is based on these posterior distributions. The integral in the denominator of equation 25 is far too complex to evaluate analytically for the delay difference model. Instead, a specific form of Monte Carlo Markov Chain (MCMC) integration, referred to as the Gibbs Sampler is used here (See Carlin et al. 1992, Carlin and Louis 1996, Meyer and Millar 1999). Bayesian modelling was carried out here using the windows version of the public domain package BUGS (WinBUGS) described in Speigelhalter et al. (1995).

Meyer and Millar (1999) suggest scaling the state equations by a constant K[3] to increase the convergence rate of the Gibbs algorithm.

$$P_t = \frac{B_t}{K} \tag{26}$$

and

$$E[B_1] = K \tag{27}$$

Therefore we will be estimating P_t, K and $r_t = R_t/K$ instead of B_t and R_t.

[3]Not to be confused with K from surplus production model.

Prior Distributions

Prior distributions are required for the proportionality constants, K, S and variance terms. Bayesian methods allow for the incorporation of prior information reflecting knowledge about the species/population based on the target population or similar populations (For fisheries examples, see Punt and Hilborn 1997). In fact, we have little information on the parameters in the model for scallops other than perhaps the expected range. The general approach in this kind of situation is to assign "non-informative" priors and let the likelihood function for the observations dominate estimation of the posterior distribution (Carlin and Louis 1996). Intuitively, this would suggest using a uniform distribution as the form for the prior thus giving each possible value of any parameter an equal chance of being chosen. Unfortunately, uniform distributions are not invariant under reparametrization and what might be non-informative on one scale may not be on another.

Alternatively, Box and Tiao (1973) suggest choosing a prior that is diffuse enough that the data will dominate whatever information there is in the prior. This is the general approach that was followed here.

The proportionality constants and the variance terms were modelled using inverse gamma distributions — the recommended form of prior for scale variables (Carlin and Louis 1996, Meyer and Millar 1999). In the context of WinBUGS the priors for the proportionality constants are written as follows.

$iq_I \sim$ gamma(0.0001, 0.0001)

$q_I \leftarrow 1/iq_I$

$iq_R \sim$ gamma(0.0001, 0.0001)

$q_R \leftarrow 1/iq_R$

This form of prior approximates a Jeffrey's prior which is both noninformative and invariant to changes in scale (Congdon 2001).

The sample variances could be calculated directly for the quantities in equations 20–23. However, for this study we set priors on the variances assuming inverse gamma distribution with the mean and variance equal and set to correspond to a coefficient of variation for the lognormal variables (fully-recruited and recruits and clapper indices) equal to 0.5. The coefficient of variation for a lognormal random variate y is $(\exp(\upsilon^2) - 1)^{0.5}$, where $\log(y)$ is a normal random variate with mean μ and variance υ^2. Therefore the coefficient of variation is independent of μ and the same expected value for υ^2 can be used for all of the variance terms in this model. A coefficient of variation of 0.5 corresponds to $\upsilon^2 = 0.22314$ which is the expected value of the inverse of a gamma distribution with parameters (3,0.44629).

Given that K was set to be the population biomass in year 1 (equation 26), a lognormal distribution was used for the prior on this parameter. In this case, the prior was set to be semi-informative with the 10% and 90% quantiles, approximately equal to 600 and 15000, respectively. That is,

$K \sim$ Lognormal(8.006, 1/1.57754)I(100, 25000).

where I(100, 25000) indicates that sampling is restricted between these lower and upper bounds.

We do have information in the literature on the separation time of the scallop hinges. Dickie (1955) reported times as short as 50 days while Merrill and Posgay (1964) suggested 231 days (33 weeks). This implies that S is between 0.14 and 0.63. We will use a uniform distribution for our prior and extend the limits to 0.10 and 0.99.

$S \sim$ uniform(0.10, 0.99).

The WinBUGS script for this model and priors is given in the Appendix 2. Note that the prior distributions require the inverse of variance or "precision" not the variances themselves.

Results

The data required for the delay-difference model are presented in Table 16 with the exception of the survey numbers for live scallops which are given in Table 14. Biomass of recruits in year t was defined as the numbers of recruits in the survey in year $t-1$ multiplied by the meat weights at shell height and then discounted for natural mortality for year t. That is, $w_k R_t$ in eqn 19 was set equal to $\exp(-M_{t-1}) w_k R_{t-1}$.

An initial run of the model indicated that the prior distributions for σ_v^2 and σ_ϵ^2 needed to be broader in range and therefore further runs were done using inverse gamma distributions with parameters (3.0, 0.89258) for the priors. These parameters correspond to an average coefficient of variation of 0.75 for the biomass of recruits and number of clappers observed in the survey.

Monitoring convergence of Gibbs Sampler

Convergence in the context of MCMC methods means that the sampled values adequately characterize the posterior distribution for any particular node or variable. Tierny (1996) presents the theoretical conditions for convergence but there is no one omnibus test for convergence and authors generally recommend using a variety of tools (Carlin and Louis 1996).

There are three aspects of an MCMC run that need to be considered. The first is to determine how many iterations it takes before the Markov chain is stationary. The samples from these preliminary iterations are considered to represent pre-convergence sampling and are discarded. The number of iterations to discard is referred to as the burn-in period for the MCMC run. Secondly, samples from MCMC methods are autocorrelated and some authors recommend subsampling every kth iteration from the converged sequence to obtain independent and identical observations for variance estimation (e.g., Raftery and Lewis 1992). This process of subsampling is referred to as thinning and the jury is still out on whether this is necessary (see pages 195–196 in Carlin and Louis 1996). The final aspect concerns how long the sampling should be conducted, that is, how many iterations are needed once the chain has converged. Again there is no one way of determining this but practical experience reported in the literature suggests monitoring the results from more than one chain with different starting values can aid in determining the rate of convergence and the number of iterations required (Gelman 1996).

One approach proposed by Raftery and Lewis (1992) uses the results from an initial MCMC run to determine the burn-in, thinning and number of iterations required to estimate a characteristic of the posterior within $\pm r$ units with probability s. An initial run of two chains of the delay difference model using the starting values in the Appendix was run for 5000 iterations with no burn-in or thinning. The Raftery and Lewis convergence diagnostic was applied to these chains with the objective of estimating the 0.025 quantile to an accuracy of ± 0.005 with probability 0.95. Software for this and other convergence statistics in S-PLUS are presented in Smith (2000). The results varied for each of the variables in the model but overall a maximum burn-in of 800 with a thinning

of 20 and a total of 3800 samples kept would cover the requirements for all of the variables in the model.

A second set of runs with burn-in = 1000, thinning = 20 and 5000 iterations kept was obtained. The results for this run appear to be more stable. Application of the Raftery and Lewis method to these data indicated that essentially no additional thinning or burn-in was required and that 5000 iterations were more than adequate. In addition, all variables from these chains passed the Heidelberger and Welch test for stationarity and the halfwidth test for adequacy of the number of iterations (Heidelberger and Welch 1983).

Model fit

A summary of the time-independent model parameters for the delay-difference model is given in Table 17. The median for the posterior distribution of K was higher than expected from the prior and the variance was less with 10 and 90 percentile being equal to 1566.0 and 4675.0, respectively compared to the the 600 and 15000 set for the prior (Fig. 20).

The likelihood was informative for the process variance term σ^2, the variance for the biomass index, σ_ε^2 and the number of live scallops in the survey, σ_φ^2. The medians from the posteriors suggests that the coefficient of variations (0.23 to 0.29) were smaller than 0.5 assumed for the prior. While the posteriors for the other two variance terms did not show much change from the priors with the posterior medians suggesting coefficients of variation of 0.55 and 0.60.

The priors for the proportionality constants were flat and the resultant posteriors indicate that the likelihood did have information on these parameters (Fig. 22). The posterior for the dissolution rate S indicates that the median time is approximately 188 days.

The residuals for the recruits and clappers were more variable than those for the process error and biomass index as expected given the posterior medians for the variance terms (Fig. 23). The large positive residuals for recruits correspond to the years with the highest recruitment (1987, 1988 and 2001). The highest residuals for clappers occurred in 1990 and 1991 which were years of high and then much lower numbers of clappers.

The significance of these apparent outliers can be evaluated by calculating the probability of getting a more extreme observation given the posterior distributions. The observed recruit biomass in 1988 stands out as being extreme with the probability of a more extreme observation being around 0.11 (Fig. 24). Such a large value is still likely given the posterior distribution but relatively rare. The clapper observations for 1990 and 1991 were flagged as being relatively extreme with both being larger than expected given the natural mortality estimates for 1989 and 1990.

A useful diagnostic for population models regardless of the estimation method used is obtained from a technique known as retrospective analysis. This method evaluates the stability of the estimates of the parameters of a model as new data are added (NRC 1998). Published results from such analysis have shown that fisheries population models can consistently under or over-estimate quantities such as biomass (Sinclair et al. 1991). We conducted a retrospective analysis of the delay-difference model used here by fitting the model to the data time series for the periods 1981–1996, 1981–1997,..., 1981–2001 and monitoring the estimates of biomass, fishing and natural mortality. The estimates from each run of the model are compared against those from the full data set (1981–2001). The model would exhibit a retrospective effect, for example, if estimates of biomass,

fishing mortality or natural mortality for 1996 in each of the time series used, deviated systematically from that obtained from the full data set. The results for the SPA 4 scallop data indicate that the delay-difference model does not exhibit any serious retrospective effects for biomass, fishing mortality or natural mortality (Figs. 25–27). This stability is very encouraging as it indicates that the projections of future population biomass from past data should also be stable.

The estimates of biomass for fully-recruited and recruits as well as natural mortality are presented in Table 17 along with 95 percent confidence limits (or referred to as credible regions in Bayesian statistics literature). Log-normal distributions were used for K, P_t and m_t and therefore larger estimates for fully-recruited and recruit biomass as well as natural mortality will also have larger variances and wider confidence limits.

Comparison between CSA and Delay-difference model

The biomass estimates for the fully recruited and recruits from the delay-difference model and from the CSA model are presented in Figs 28 and 29, respectively. We had noted earlier that we could not estimate both catchabilities q_R and q_I, or natural mortality from the data using the CSA model. Therefore, the CSA model was fit to the data using the mortality estimates in Table 17 and assuming $q_R = q_I/1.43$ as per the selectivity results.

While the biomass estimates from the two models followed similar trends, there were differences which were especially pronounced during the years of strong recruitment and high population biomass. Much of the data used by the two methods were the same including the average weight for fully-recruited and recruits. However, the catchability coefficient estimates differ between the two models. The catchability estimate for fully-recruited biomass CSA model (0.1139) was about half that from the delay-difference model (0.2279). The CSA catchability coefficient for recruits was 0.0797 (0.1139/1.43) compared to 0.0941 for the delay-difference model.

Bootstrap confidence intervals were computed for the CSA estimates of fully-recruited and recruits (Table 15). The confidence intervals appear to be relatively narrower than those for the delay difference model in Table 17. It is difficult to accept that the former model is more precise than the latter given the similar data sets being used.

Discussion

State-Space models

Both the CSA model and the delay-difference model were expressed as state-space models. State-space models are not commonly used in fisheries modelling and the concept of a process error may be unfamiliar to many fisheries researchers. In these kinds of models the current state of the process summarizes all of the information from the past that is necessary for predictions of future states (Abraham and Ledolter 1983). The measurement equations (e.g., equations 20–23) describe the generation of observations from the current state with measurement error. The system equation (e.g., equation 19) describes how the states are supposed to evolve through time with random shocks[4] captured by the process error. In the extreme, if there is no process error, the state-space model reduces to a regression model with measurement error only. On the other hand,

[4]Random shocks are used in a time series sense and could refer to environmental variation, etc.

with no measurement error, the state space model simplifies to a multivariate version of a first-order autoregressive time-series model. Therefore, the measurement error characterizes our uncertainty with respect to the current state, while the process error captures the uncertainty moving from the current state to the next one in time. Our experience with this kind of model to date suggests that the process error term is a reasonable component of a model given the time series nature of the data.

Comments on natural mortality

Most fishery models assume a constant and known level of natural mortality. This scallop fishery is very unique in that we have a well recognized proxy for natural mortality — clappers. Natural mortality in scallops has been attributed to temperature fluctuations, siltation, oxygen depletion, damage due to dredges in addition to predation and parasites (Young-Lai and Aiken 1986). Mass mortalities have been recorded for sea scallops throughout the Gulf of St. Lawrence, Bay of Fundy and Georges Bank (Dickie and Medcof 1963, Merrill and Posgay 1964, Kenchington et al. 1995). Dickie and Medcof (1963) suggested that sudden increases in water temperature due to wind-driven depth changes in the thermocline were responsible for mass mortalities in the Gulf of St. Lawrence. Temperature changes have not been identified as the cause for mass mortalities in the Bay of Fundy.

Medcof and Bourne (1964) studied the condition of discarded scallops that suffered damage mechanically in the dredge and through air exposure. These authors noted that based on their experience with the increased catches in 1959 in the Bay of Fundy that a higher rate of damage occurred during periods of high catch rates. Caddy (1973) estimated that incidental mortality due to fishing may be as high as 13–17 percent per tow.

Both Dickie and Medcof (1963) and Medcof and Bourne (1964) reported that damaged scallops were observed suffering high predation mortality by predators. Citing laboratory studies by others and personal experience, these authors stated that starfish were attracted to damaged scallops. Caddy (1973) reported that predators were attracted to dredged areas within one hour of fishing and densities increased by 3 to 30 times over that observed in undredged areas. In a recent study, Veale et al. (2000) report that densities of scavenger species increased by up to 200 times that of the background density and persisted for up to three days after scallop dredges had passed through an area. Starfish (*Asterias rubens*) were observed attacking undamaged queen scallops (*Aequipecten opercularis*, L.) as often as damaged scallops in the dredged area. Jenkins and Brand (2001) demonstrated that dredging or exposure to air or both, resulted in a decreased swimming ability of great scallops (*Pecten maximus*, L.) and hence limited the animals ability to escape predators. These negative effects could last up to 24 hours after the dredging or exposure.

When the mass mortality event was observed in the Bay of Fundy in 1989 and 1990, many fishermen suggested that starvation was the cause because of the high numbers of scallops recruiting from the 1984 and 1985 year-classes. Robinson et al. (1992) reports that the industry applied pressure to fishery managers to lift restrictions on catch levels so that as much harvest could be taken before all of the yield was lost to natural mortality. There were no samples of scallops taken in 1989 to investigate the possible causes of this catastrophic mortality. Based upon RNA/DNA ratios taken from scallops in 1990, Robinson et al. (1992) were unable to find any indication of starvation in the scallop populations in the Cape Spencer, Grand Manan or Passamaquoddy area.

The delay-difference model estimated that natural mortality increased after catches began to dramatically increase in 1987/1988 and 1988/1989 (Fig. 30). Our estimates indicate that the 1998

year-class may be the most abundant year-class next to the record 1984 year-class. We have had no indication from the monitoring surveys that there has been an increase in natural mortality yet (Table 20). In addition, a comparison of the percentage of clappers in the area being heavily fished at present (Above Digby Gut) to those observed in the lightly fished area below Digby Gut does not seem to indicate that the current fishing effort has resulted in increased numbers of clappers. We will be continuing the monitoring surveys for at least 2002.

Management Implications

The main message of this assessment is that the estimated biomass of fully-recruited scallops (shell height 80 mm and greater) in SPA 4 is the third highest in the series since 1981. Similarly, the recruitment biomass is the second highest in the series after that estimated for 1988. Catch levels are already higher than they have been for the last 10 years and are expected to continue to increase or remain high for the next few years.

Samples taken from the area by the J.L. Hart and the F.V. Julie Ann Joan indicate that the 1998 year-class is growing faster than expected with around 75 percent exceeding 80 mm (3.1 inch) shell height (Table 8) by November 2001. Based on the growth characteristics of earlier year-classes we would have expected that the animals would not be at this stage until spring 2002. However, the scallops were reaching meat weights of 8–9 g (63 to 56 count) in November of 2001. These weights (and shell heights) are expected to change little until late spring when the phytoplankton bloom starts. The meat weights for this year-class should be around 12–14 g (42 to 36 count) in the fall of 2002 but as we say above, their growth has been atypically fast and they could be somewhat heavier.

While the potential of a high mortality event such as that experienced in 1989/90 is on everyone's mind, we have not seen any evidence of increasing natural mortality yet. If we assume that this continues to be the case then there may be some advantage in trying to increase the spawning stock biomass. While we can't be sure that all of the larvae spawned in SPA 4 return to the same area, these and the neighbouring beds in SPA 1 have been persistent through time and it would be hard to believe that increased spawning biomass in both areas would not benefit both of these areas as well. It is likely that successful settlement of larvae is as much a function of favourable environmental conditions as anything else. Having higher densities of spawn in the water would ensure that adequate numbers survive when conditions are poor or that more than adequate numbers are available when conditions are good. In the end, there is the potential for more regular recruitment over time.

There are no objectives and associated reference points presently defined for this fishery. During the RAP meeting we proposed the following approach to setting objectives and using the delay-difference model to evaluate future harvests against these objectives. This approach was introduced to initiate discussions with the fishing industry and fisheries management on how to define objectives. The details of this approach were included in the stock status report (DFO 2002) but the method was not used to provide advice to the fishing industry.

If we define our objective to be one of increasing the spawning stock then this could be achieved by fishing below traditional robust limits for growth overfishing such as $F_{0.1}$. Fishing below this target also allows enough scallops to get larger to increase spawning output. A first cut at estimating the $F_{0.1}$ for this stock from yield-per-recruit analysis puts it at 0.14 assuming natural mortality equal

to the estimated average in recent years of 0.10. Evaluation of potential catch levels would be made with respect to whether or not these catches resulted in fishing mortalities being above or below 0.14. Our estimates of population size and current fishing mortality are based on the surveys and commercial catches, and as a result, they have uncertainty associated with them. Consequently, it would be misleading to give a single number only for estimated fishing mortality. Instead we use the posterior probabilities associated with the fishing mortality to state the probability that the proposed catch level results in a fishing mortality in excess of 0.14.

In assessing the impact of the preliminary TAC of 300 t for the 2001/02 season we estimated the median fishing mortality that this catch would imply as 0.12 (Table 21) assuming that natural mortality this year will be the same as last year. Based on the model we are using, the probability of the fishing mortality from this catch exceeding 0.14 is 0.35. That is, while we believe that the median fishing mortality was 0.12, there was a 35 percent chance that fishing mortality was actually higher than 0.14. The smaller the probability of being greater than 0.14 the more certain we are that the catch of 300 t did not result in a fishing mortality higher than our target. Note that a higher catch of 350 t increases our uncertainty that fishing mortality was lower than 0.14 and the probability of 0.50 indicates that we are equally likely to be above the target as to be below.

Apparently, there is little influence of catching anywhere from 300 to 500 t in 2001/02 on what could be caught in 2002/03. This is mainly due to the large size of the recruiting year-class. However, larger catches in 2001/02 would probably result in an increase in meat count for catches in 2002/03. The impact of natural mortality being higher in the next two years than estimated for 2000/2001 was evaluated in Table 22 by setting the natural mortality for 2001/2002 and 2002/2003 at 0.21. Again, higher catches in 2002/2003 than in 2001/2002 are still possible because of the large year-class.

Limiting catches in 2001/02 could leave more larger scallops in the fishery for the fall of 2002 and result in lower meat counts. Resource Allocation chose to go with 400 t for the TAC increase in December for the 2001/2002 season based on the strength of the 1998 yearclass and its impact on what could be available for 2002/2003.

Since 1981, the population has exhibited a boom or bust type of pattern with there being low catches and low biomass most years with occasional episodic recruitment (Fig. 31). Based on this very short history, we do not know what the carrying capacity of the scallop population in SPA 4 area is or if the larger biomass resulting from the recent high recruitment will be sustainable. The above approach to evaluating catch levels implicitly assumes that the higher population biomass is sustainable.

An alternative approach is to treat years in which episodic recruitment (peak years) occurs separately from the other years (non-peak years). Using the average natural mortality from the population model (omitting 1989 to 1991), yield-per-recruit analysis predicts that $F_{0.1}$ would be (0.15). This implies an average catch of 337 t and an average population biomass of 2300 t for the average recruitment during the non-peak years. During those same years the population model predicted that the average fishing mortality was 0.21 with an average catch of 360 t and average population biomass of 1898 t. These compare well with the yield-per-recruit predictions of average catch and biomass for $F = 0.21$ of 383 t and 1896 t, respectively. Therefore, the yield-per-recruit dynamics seem to be in agreement with our population model and we could set 2300 t as our target population biomass during non-peak years (Fig 31).

For the peak years we suggest evaluating catch levels based upon how long we can expect the large year-class to last with the bottom line that we do not wish to see the catch drive the population biomass below the 2300 t limit. We use this approach first for the current season and then for future seasons conditional on what was finally set for the 2001/2002 season (Table 23). These projections were calculated assuming average non-peak recruitment, mortality and growth. The median posterior estimate of the 2002 biomass was above the 2300 t mark for catches ranging from 400 to 600 t in 2001/2002. The probability of biomass in 2002 exceeding 2300 t was greater than 0.94 in all cases. Landings of 1000 to 2000 t were considered for 2002/2003. Catches of 1000 to 1500 t per year for 2002/2003 to 2004/2005 did not result in the median biomass falling below 2300 t no matter whether 400 or 800 t was caught in 2001/2002. However, a catch of 2000 t over the next three seasons did run into this problem in the third year.

However, it is more important to pay attention to the probabilities of the catches causing the population biomass to fall below 2300 t, because these reflect our uncertainties. While the TAC for 2002/2003 does not have to be agreed upon until later in 2002, the fishing industry and management should start to consider how much uncertainty they are willing to live with. Tests of scientific hypotheses tend to use the 0.01 to 0.05 level for uncertainty in the scientific literature. Similar evaluations in the health field tolerate only very small (less than 0.001) levels of uncertainty. The fishing industry may be willing to tolerate higher levels of uncertainty.

For the moment, assume that 0.25 is a reasonable level of uncertainty, then we would recommend all catch levels in Table 23 where the probability of the biomass being below 2300 t is less than 0.25. Also assume that the fishing plan is to be constructed such that a catch level is recommended for 2001/2002 and conditional on that level, a recommendation is made for a constant catch level for the next two or three seasons. Keeping the current TAC in 2001/2002 at 400 t would permit a catch of 1000 t for the next three seasons but the higher catches would be limited to the next two or one seasons. Catches of 600 to 800 t in 2001/2002 would imply an in-season increase and would permit catches of 1000 t for the next two years. Higher catches of 1500 t would not be for more than one year. Based on our criterion of 0.25 probability, catches of 2000 t in subsequent years would not be recommended.

The second approach detailed above was presented to the scallop industry at the March 22, 2002 meeting of the Inshore Scallop Advisory Committee (ISAC). Based on the information presented, ISAC recommended an increase to the 2001/2002 season TAC to 650 t with a preliminary TAC of 1000 t set for 2002/2003. We will assess the accuracy of our probability estimates in Table 23 and verify our model predictions after the June 2002 survey has been completed. We will also need more discussion on the appropriate levels of uncertainty to use. The final TAC for 2002/2003 will be established with ISAC after this analysis has been completed and before the season starts on 1 October, 2002.

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Appendix 1: Popcorn model[5]

Clappers are assumed to have a fixed "lifespan". Let S be the separation time as a fraction of a year of a clapper, $M(t)$ be natural mortality and let $Z(t)$ and $L(t)$ be the clapper and live population at time t. Then,

$$Z(t) = \int_{t-S}^{t} M(\tau)L(\tau)d\tau \tag{28}$$

Consider the equilibrium case where M and L are constants. Then,

$$Z = MLS \tag{29}$$

solving for M ,

$$M = \frac{Z}{LS} \tag{30}$$

and M is proportional to the clapper ratio estimate of Dickie (1955) and Merrill and Posgay (1964).

When system is not in equilibrium it is not necessary to approximate the functions $L(t)$ and $M(t)$. Practically, t is known only at integer times (every June) and M was assumed to be a constant M_t during any year t. Also, experimental evidence indicates that $S < 1$. In such a case, $L(\tau)$ can be approximated linearly from $L(t) = L_t$ and $L(t-1) = L_{t-1}$.

$$L(\tau) = (t-\tau)L_{t-1} + (1-t+\tau)L_t \tag{31}$$

Substituting this into equation (28) gives,

$$\begin{aligned}
Z_t &= M_t \int_{t-S}^{t} \left[(t-\tau)L_{t-1} + (1-t+\tau)L_t\right] d\tau \\
&= M_t \left[(t\tau - \tau^2/2)L_{t-1} + (\tau - t\tau + \tau^2/2)L_t\right]\Big|_{t-S}^{t} \\
&= M_t \left[\left[t^2 - t^2/2 - t(t-S) + (t-S)^2/2\right] L_{t-1}\right. \\
&\quad \left. + \left[t - t^2 + t^2/2 - (t-S) + t(t-S) - (t-S)^2/2\right] L_t\right] \\
&= M_t \left[\left(-t^2/2 + tS + t^2/2 + S^2/2 - tS\right) L_{t-1}\right. \\
&\quad \left. + \left(-t^2/2 + S - ts - t^2/2 - S^2/2 + tS\right) L_t\right] \\
&= M_t \left[S^2 L_{t-1}/2 + \left(S - S^2/2\right) L_t\right] \\
&= \frac{S}{2} M_t \left[S L_{t-1} + (2-S) L_t\right]
\end{aligned} \tag{32}$$

[5]The derivation of this model was provided by D. Hart (NMFS, Woods Hole).

Appendix 2: Script for WinBUGS version of Delay Difference Model

```
Biomass Dynamic model
 SPA 4 scallops 1981 to 2001

model;
 {

# Process equations (Catch at beginning of year)
########################

Pmed[1] <-0

for (i in 2:NY) {
    Pmed[i]<-log(max(exp(-m[i])*(rho+alpha/w[i-1])*(P[i-1]-Catch[i-1]/K)
             +exp(-m[i])*rp[i-1],0.01))
    }


for(i in 1:NY){
    P[i]~dlnorm(Pmed[i],isigma)I(0,5)
}

#Observation equations
 ########################

#Survey Biomass

for(i in 1:NY){
    Imed[i]<-log(qI*K*P[i])
        I[i]~dlnorm(Imed[i],ivarepsilon)
}

#Survey numbers

for(i in 1:NY){
    Lmed[i]<-log(qI*K*P[i]/(w[i]/pow(10,6)))
        L[i]~dlnorm(Lmed[i],itau)
}


#Survey recruitment

for(i in 1:NY){
        rp[i]~dlnorm(-1.9,0.5)I(0,6)
}

for(i in 1:NY){
    Rmed[i]<-log(qR*K*rp[i])
        R[i]~dlnorm(Rmed[i],inu)
}
```

```
#S=dissolution rate in days/365

S~dunif(0.10,0.99)

for(i in 1:NY){
        m[i]~dlnorm(-1.9,0.5)I(0,4)
}


#Natural mortality from survey clapper index, using popcorn model

cmed[1]<-log(m[1]*S*L[1])

for(i in 2:NY){
   cmed[i]<-log(m[i]*S*(S*L[i-1]+(2-S)*L[i])/2)
         }

for(i in 1:NY){
 clappers[i]~dlnorm(cmed[i],iepsilon)
  }


#Distribution of K
 ############################

K~dlnorm(8.006,0.63390)I(500,25000)

#Distribution of q's
 ############################

iqI~dgamma(0.0001,0.0001)

qI<-1/iqI


iqR~dgamma(0.0001,0.0001)

qR<-1/iqR

#Distribution of variance terms
 ############################

isigma~dgamma(3,0.44639)
 sigma<-1/isigma

itau~dgamma(3,0.44639)
 tau<-1/itau

ivarepsilon~dgamma(3,0.44639)
 varepsilon<-1/ivarepsilon

inu~dgamma(3,0.89258)
```

```
 nu<-1/inu

iepsilon~dgamma(3,0.89258)
 epsilon<-1/iepsilon

# Output
 ##############################

for(t in 1:NY){
  biomass[t]<-P[t]*K
 }

for(t in 1:NY){
  Ipred[t]<-P[t]*K*qI
   }

for(t in 1:NY){
 Rec[t]<-rp[t]*K
  }

#Diagnostics
 ################################################

for(i in 1:NY){
    resid.p[i]<-log(P[i])-Pmed[i]
    sresid.p[i]<-resid.p[i]*sqrt(isigma)
    resid.I[i]<-log(I[i])-Imed[i]
    sresid.I[i]<-resid.I[i]*sqrt(ivarepsilon)
    resid.R[i]<-log(R[i])-Rmed[i]
    sresid.R[i]<-resid.R[i]*sqrt(inu)
    resid.c[i]<-log(clappers[i])-cmed[i]
    sresid.c[i]<-resid.c[i]*sqrt(iepsilon)
    resid.L[i]<-log(L[i])-Lmed[i]
    sresid.L[i]<-resid.L[i]*sqrt(itau)
    }

for(i in 1:NY){
          I.rep[i]~dlnorm(Imed[i],ivarepsilon)
       p.I.smaller[i]<-step(I[i]-I.rep[i])
          L.rep[i]~dlnorm(Lmed[i],itau)
       p.L.smaller[i]<-step(L[i]-L.rep[i])
       R.rep[i]~dlnorm(Rmed[i],inu)
       p.R.smaller[i]<-step(R[i]-R.rep[i])
      clappers.rep[i]~dlnorm(cmed[i],iepsilon)
       p.clappers.smaller[i]<-step(clappers[i]-clappers.rep[i])
}}
```

Starting values for Gibbs sampler

Chain 1

```
list(P=c(0.70,0.65,0.60,0.55,0.50,0.45,0.40,0.35,0.30,0.30,
0.70,0.65,0.60,0.55,0.50,0.45,0.40,0.35,0.30,0.3,0.1),
isigma=100,ivarepsilon=1,inu=1,iqI=5,iqR=5,iepsilon=1,
itau=1,S=0.2,K=600,m=c(0.9,0.9, 0.9, 0.9, 0.9, 0.9, 0.9,
 0.9, 0.9,0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9,
0.9,0.9),rp=c(0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2,
0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2,0.2))
```

Chain 2

```
list(P=c(0.42, 0.48, 1.02, 1.28, 0.73, 0.28, 0.87, 0.12, 0.04,
1.33, 0.25, 1.55, 0.68, 0.35, 1.26, 0.76, 1.28, 0.72,
1.93,0.85,3.0),isigma=1,ivarepsilon=100,inu=100,itau=100,iqR=500,
iqI=500,iepsilon=100,S=0.7,K=19000,m=c(0.1, 0.1, 0.1, 0.1, 0.1,
0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1, 0.1,0.1, 0.1, 0.1, 0.1, 0.1,
0.1, 0.1, 0.1,0.1),rp=c(0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9,
0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9, 0.9,0.9))
```

Table 1. Reconstruction of the landings (meats, t) history of scallop fishery within Scallop Production Area (SPA) 4 from 1976 to the present in the Bay of Fundy. See text for details. Results for 2001–2002 season are preliminary as of 28/01/2002. The total column refers to annual totals.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
1976	0.0	1.4	21.6	102.8	9.0	22.4	17.7	14.6	26.1	32.7	6.3	1.0	255.7
1977	3.9	8.3	41.5	77.5	46.8	39.0	33.3	51.2	27.5	77.5	36.8	5.7	448.9
1978	0.9	9.3	33.7	89.7	21.6	10.8	15.5	26.9	19.8	101.7	29.8	0.9	360.7
1979	1.9	1.6	43.1	72.4	18.8	9.5	4.6	11.5	4.2	80.0	30.4	2.6	280.8
1980	9.0	15.4	51.9	106.4	42.9	23.4	13.6	8.3	22.4	112.8	29.2	15.5	450.8
1981	9.6	47.2	83.6	61.3	29.1	22.0	21.1	14.6	28.0	149.1	36.2	13.4	515.5
1982	6.6	26.8	103.8	47.9	33.3	42.5	9.3	25.5	59.2	181.0	72.3	16.2	624.3
1983	20.5	32.2	52.4	77.0	36.5	30.7	43.5	23.8	16.4	112.0	42.2	14.0	501.3
1984	22.1	35.8	30.4	42.4	40.6	13.9	19.6	13.3	8.6	83.7	37.7	10.9	358.8
1985	13.7	24.7	24.9	56.4	18.9	11.9	20.4	24.0	22.9	62.7	26.8	10.8	318.1
1986	6.3	27.1	24.0	15.7	3.2	1.7	2.7	2.5	7.3	22.3	10.3	7.5	130.6
1987	2.9	1.0	1.1	13.8	7.0	0.0	0.0	0.5	0.0	169.6	84.9	104.6	385.5
1988	107.6	187.5	139.7	155.4	64.9	73.7	36.5	62.1	22.2	662.3	363.5	212.8	2088.1
1989	413.9	378.3	346.4	345.7	38.4	57.2	16.6	0.0	0.0	271.4	46.8	2.3	1917.1
1990	7.2	0.0	4.2	6.5	0.4	1.5	0.0	0.0	7.6	185.0	68.7	24.4	305.5
1991	65.6	93.9	59.3	102.3	15.4	7.5	7.2	23.5	26.3	171.7	52.5	11.4	636.6
1992	19.6	37.5	37.1	27.1	1.5	0.9	2.4	4.3	7.3	136.7	45.0	11.6	331.0
1993	11.0	9.7	33.2	22.5	7.8	0.0	0.0	3.0	5.2	107.8	34.5	16.7	251.4
1994	3.3	11.3	12.6	14.2	2.3	0.0	9.1	13.6	5.5	85.6	13.7	6.7	177.9
1995	15.1	9.2	17.6	22.7	9.0	0.8	11.2	10.7	6.8	9.8	4.7	2.7	120.3
1996	3.8	4.5	6.7	2.4	4.1	5.2	9.6	10.1	2.6	0.0	44.6	16.2	109.7
1997	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	104.3	8.9	2.9	116.1
1998	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.7	36.0	13.5	4.6	106.8
1999	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	38.1	20.5	18.0	76.7
2000	5.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	61.4	7.8	2.3	77.5
2001	4.0	1.3	0.3	0.0	11.3	0.5	0.2	0.6	0.0	78.5	66.8	50.2	213.7
2002	29.3												

Table 2. Reconstruction of the history of scallop fishery within Scallop Production Area (SPA) 4 from 1976 to the present in the Bay of Fundy. Class 1 data refers to records from logbooks for the Full Bay fleet where catch, location and effort were all reported. Total effort and landings were calculated from logbook data and total catch reported for the Bay of Fundy (see text for details). The fishing season was defined to be from 1 October in year t to 30 September in year $t + 1$. The one exception to this is the 1998-1999 season which opened on 22 September 1998. Results for the 2001–2002 season are preliminary as of 28 January, 2002. The TAC of 400 t was set in December 2001 and in-season increases could still be discussed.

	Class 1 Data			Total		
Season	CPUE (kg/h)	Effort ('000 h)	Catch (meats, t)	Effort ('000 h)	Landings (meats, t)	TAC (meats, t)
1976-1977	33.34	5.81	193.53	11.07	368.98	
1977-1978	37.55	6.00	225.48	9.27	348.22	
1978-1979	34.53	6.56	226.66	8.70	300.27	
1979-1980	36.52	9.00	328.61	11.12	406.25	
1980-1981	38.25	9.52	364.34	12.39	474.14	
1981-1982	36.56	11.42	417.56	15.14	553.69	
1982-1983	29.30	15.27	447.31	20.57	602.62	
1983-1984	18.66	16.99	316.98	21.15	394.58	
1984-1985	14.44	19.50	281.45	24.25	350.12	
1985-1986	12.22	10.05	122.87	15.61	190.81	
1986-1987	9.92	2.41	23.93	6.71	66.52	
1987-1988	57.70	2.14	123.22	20.94	1208.56	
1988-1989	97.56	2.26	220.83	29.06	2835.25	
1989-1990	47.07	0.59	27.88	7.39	347.83	
1990-1991	31.48	3.48	109.41	21.57	679.19	
1991-1992	20.74	3.88	80.46	18.00	373.39	
1992-1993	16.35	4.55	74.35	17.47	285.68	
1993-1994	12.74	5.98	76.13	18.11	230.80	
1994-1995	10.27	8.26	84.74	20.38	209.18	
1995-1996	7.52	2.20	16.55	8.78	66.02	
1996-1997	8.69	5.54	48.20	6.99	60.80	
1997-1998	12.65	7.01	88.64	9.18	116.14	100
1998-1999	9.60	10.62	101.95	11.13	106.82	120
1999-2000	8.98	7.80	70.10	8.54	76.70	120
2000-2001	16.16	5.88	95.03	6.31	102.05	110
2001-2002	46.76	4.18	195.47	4.37	243.00	400

Table 3. Results from fitting a standardization model to the catch rate data from Scallop Production Area 4, Seasons 1975–76 to 2001–2002. a) Analysis of variance table. b) Predicted catch rate for October with 95 percent confidence intervals.

a) ANOVA table

Term	Df	Sum of Squares	Mean SS	F	Pr(F)
Months	11	109.4	9.95	65.03	0
Season	26	1547.5	59.52	389.05	0
Residuals	4420	676.2	0.15		

b) Predicted cpue (kg/h)

Season	Prediction	Lower Limit	Upper Limit
1975-1976	32.18	28.69	36.22
1976-1977	52.56	48.78	56.72
1977-1978	52.39	49.14	55.91
1978-1979	44.29	41.58	47.23
1979-1980	47.46	44.94	50.16
1980-1981	50.95	48.38	53.68
1981-1982	46.61	44.28	49.09
1982-1983	36.83	35.09	38.68
1983-1984	24.74	23.62	25.93
1984-1985	18.98	18.10	19.91
1985-1986	14.59	13.77	15.46
1986-1987	11.85	10.68	13.19
1987-1988	77.89	70.40	86.41
1988-1989	104.14	93.78	115.98
1989-1990	43.73	36.61	52.68
1990-1991	36.28	32.79	40.26
1991-1992	23.25	21.38	25.33
1992-1993	19.09	17.47	20.91
1993-1994	15.60	14.43	16.88
1994-1995	12.08	11.27	12.96
1995-1996	9.38	8.44	10.46
1996-1997	9.82	9.12	10.57
1997-1998	12.47	11.63	13.39
1998-1999	10.91	10.26	11.61
1999-2000	9.75	9.15	10.41
2000-2001	14.61	13.40	15.96
2001-2002	55.75	51.76	60.13

Table 4: Statistics from meat weight samples from Full Bay fleet scallop vessels in Scallop Production Area 4. Samples from 1983 to 1999 were obtained from departmental program. Samples from 2000 to present were collected by the industry supported dockside monitoring program.

			Meat Weight (g)			Count	Number of
Year	Month	N	Mean	Min.	Max.	per 500 g.	Samples
1983	May	1621	11.0	2.4	29.6	45.9	19
1983	Jun	530	12.4	2.2	29.4	41.3	7
1983	Jul	1477	12.7	3.3	45.8	39.6	20
1983	Aug	1521	13.0	3.4	28.8	38.9	21
1984	Apr	1418	18.1	2.1	50.5	28.5	25
1984	May	3533	12.5	2.2	30.2	40.3	44
1984	Jun	1164	11.4	2.8	29.7	45.1	13
1984	Jul	2811	13.2	2.2	38.6	38.5	37
1984	Aug	1656	13.1	2.4	42.4	39.5	22
1984	Sep	990	14.7	4.1	43.9	35.3	14
1984	Oct	2200	23.3	3.8	57.9	21.8	50
1985	Apr	503	18.8	3.4	52.3	28.0	9
1985	May	1284	14.2	3.1	35.8	35.7	18
1985	Jun	467	13.4	3.3	27.5	38.7	6
1985	Jul	2631	13.3	2.4	33.4	38.6	34
1985	Aug	1695	16.9	3.2	38.8	30.2	28
1985	Sep	2363	13.3	2.5	35.8	38.1	31
1985	Oct	809	26.4	5.4	51.2	19.3	21
1986	May	642	10.9	2.0	31.5	46.7	7
1986	Jun	1070	11.4	2.3	27.0	44.8	12
1986	Jul	1575	9.9	2.1	26.2	52.7	15
1986	Aug	985	10.5	2.5	24.6	49.2	10
1986	Sep	1655	11.9	3.3	43.1	45.9	18
1986	Oct	1302	21.0	2.1	52.3	25.9	25
1987	Oct	3215	9.1	2.3	50.1	55.2	29
1988	May	1185	6.1	2.1	33.6	84.4	7
1988	Aug	117	8.6	4.8	21.7	58.2	1
1988	Oct	3769	12.5	3.0	43.7	40.8	46
1988	Nov	1100	13.9	5.0	46.6	36.3	15
1989	Apr	103	9.8	4.9	21.6	51.3	1
1989	May	102	9.9	4.2	20.1	50.6	1
1989	Sep	656	6.1	3.7	19.2	81.7	4
1989	Oct	1802	19.0	2.1	53.6	29.1	31
1990	Jun	95	10.7	4.3	23.8	46.6	1
1990	Jul	88	11.3	2.1	23.2	44.4	1
1990	Aug	124	17.2	7.0	37.6	30.7	2
1990	Sep	224	13.5	6.1	22.6	37.1	3
1990	Oct	1197	24.2	6.3	60.4	21.3	28
1990	Nov	39	25.4	13.6	42.7	19.7	1

Table 4: SPA 4 Meat weight statistics, cont'd.

			Meat Weight (g)			Count	Number of
Year	Month	N	Mean	Min.	Max.	per 500 g.	Samples
1991	May	260	16.9	4.2	32.0	32.2	4
1991	Aug	72	14.1	7.8	27.3	35.5	1
1991	Sep	93	21.8	7.8	36.3	23.0	2
1991	Oct	744	27.3	6.0	57.0	19.5	19
1992	Aug	111	18.8	7.2	40.8	27.7	2
1992	Sep	79	29.7	9.1	55.9	16.8	2
1992	Oct	2357	18.8	3.7	66.2	30.0	37
1992	Nov	1358	24.8	4.8	79.5	22.5	26
1992	Dec	675	27.1	4.3	62.5	19.1	15
1993	Jan	1064	21.6	2.3	54.9	25.4	20
1993	Feb	996	16.6	4.3	52.7	32.0	13
1993	Mar	1034	15.8	4.9	41.2	32.8	14
1993	Apr	49	22.3	5.8	37.2	22.4	1
1993	May	198	11.3	2.6	25.7	50.1	2
1993	Jun	144	14.0	4.5	29.5	36.0	2
1993	Oct	1080	23.5	6.8	57.4	23.0	22
1993	Nov	559	26.5	8.3	50.6	19.4	15
1993	Dec	367	21.8	6.9	40.9	24.3	7
1994	Jan	94	23.0	8.7	40.4	21.8	2
1994	Feb	265	21.5	6.2	44.3	26.6	5
1994	Aug	74	14.9	4.1	26.1	33.5	1
1994	Oct	523	16.4	4.5	46.3	33.0	7
1994	Nov	59	17.3	11.2	28.4	28.8	1
1994	Dec	505	14.2	4.6	36.8	36.4	6
1995	Jan	89	37.0	15.1	63.5	13.6	3
1995	Mar	217	15.5	5.0	39.5	32.2	3
1996	Jan	133	19.3	4.6	37.0	27.2	2
1996	Feb	471	21.4	4.4	43.8	26.2	12
1996	Mar	322	20.5	4.3	38.7	26.4	7
1996	Oct	167	6.1	3.7	12.3	82.0	1
1996	Nov	1250	20.3	4.0	49.7	35.6	17
1996	Dec	584	23.3	5.5	46.8	22.9	13
1997	Oct	1168	21.4	7.1	45.4	24.3	23
1997	Nov	193	14.5	6.3	29.7	34.8	3
1998	Sep	282	25.9	8.7	45.9	20.1	6
1998	Oct	331	23.6	7.9	49.2	21.7	7
1998	Nov	177	24.5	11.5	61.3	20.7	4
1998	Dec	355	23.7	15.4	42.5	21.3	7
1999	Oct	296	24.3	16.5	44.0	20.8	7
1999	Nov	205	22.3	8.4	49.4	23.0	4

Table 4: SPA 4 Meat weight statistics, cont'd.

			Meat Weight (g)			Count	Number of
Year	Month	N	Mean	Min.	Max.	per 500 g.	Samples
1999	Dec	468	23.5	8.7	49.6	21.8	10
2000	Jan	443	31.5	9.7	56.8	16.4	13
2000	Oct	1775	17.2	4.7	48.7	30.0	29
2000	Nov	144	21.4	8.8	47.5	23.6	3
2001	Feb	38	26.4	9.8	50.1	18.9	1
2001	Mar	33	30.7	13.0	60.3	16.3	1
2001	May	441	16.4	5.9	46.5	30.7	7
2001	Jun	59	16.6	9.9	27.4	30.1	1

Table 5. Average meat weight (g) by month from sampling of commercial scallop catch from Scallop Production Area (SPA) 4 from 1976 to the present in the Bay of Fundy. See text for details. Annual estimates are based on an average of monthly estimates weighted by monthly catch from Table 1.

Year	Jan.	Feb.	Mar.	Apr.	May	Jun	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1983					11.0	12.4	12.7	13.0					12.2
1984				18.1	12.5	11.4	13.2	13.1	14.7	23.3			17.8
1985				18.8	14.2	13.4	13.3	16.9	13.3	26.4			19.0
1986					10.9	11.4	9.9	10.5	11.9	21.0			16.7
1987										9.1			9.1
1988					6.1			8.6		12.5	13.9		12.4
1989				9.8	9.9				6.1	19.0			13.6
1990						10.7	11.3	17.2	13.5	24.2	25.4		24.1
1991					16.9			14.1	21.8	27.3			24.7
1992								18.8	29.7	18.8	24.8	27.1	21.0
1993	21.6	16.6	15.8	22.3	11.3	14.0				23.5	26.5	21.8	21.9
1994	23.0	21.5						14.9		16.4	17.3	14.2	16.8
1995	37.0		15.5										25.5
1996	19.3	21.4	20.5							6.1	20.3	23.3	20.9
1997										21.4	14.5		20.8
1998									25.9	23.6	24.5	23.7	24.8
1999										24.3	22.3	23.5	23.6
2000	31.5									17.2	21.4		18.7
2001		26.4	30.7		16.3	16.6				14.6	12.6	12.2	13.6
2002	11.1												

Table 6. Statistics on meat weight samples from Full Bay fleet scallop vessels in Scallop Production Area 4 for the 2001/2002 fishing season. All samples collected by industry supported dockside monitoring program. Statistics on the percentage by number of meats in the sample that were less than 8 g are also given.

			Meat Weight (g)			Count	Number of	Percent < 8 g		
Year	Month	N	Mean	Min.	Max.	per 500 g.	Samples	Mean	Min.	Max.
2001	Oct	2092	14.6	6.3	47.3	34.3	30	0.8	0.0	4.3
2001	Nov	2812	12.6	5.9	90.0	39.6	35	2.9	0.0	13.1
2001	Dec	1092	12.2	5.0	46.3	41.1	13	5.7	0.0	16.3
2002	Jan	1211	11.1	4.6	45.5	45.0	15	7.4	0	25.5

Table 7. Estimates from stratified research survey for scallops in Scallop Production Area 4, June 2001. Proportion of survey area in each stratum is given in the second column. Estimates of mean number are given for three shell height size classes roughly corresponding to pre-recruit, recruits and fully-recruited animals.

			< 40 mm		40 to 79 mm		80+ mm	
Stratum Name	Propn. area in stratum	Number of Tows	Mean number	Standard error	Mean number	Standard error	Mean number	Standard error
Centreville	0.133	11	28.29	17.32	144.12	58.71	123.76	15.77
CV to GH	0.068	5	11.28	9.32	117.58	72.50	84.58	39.20
Gulliver's Head	0.133	14	28.96	9.73	1762.34	391.71	317.72	73.55
GH to DG	0.100	10	8.45	4.03	1012.39	379.85	414.61	225.65
Digby Gut	0.200	19	51.61	16.22	1521.61	327.47	1302.32	306.70
DG to DC	0.100	9	31.88	26.85	913.30	297.17	1045.86	504.43
Delaps Cove	0.133	12	19.01	6.47	1083.96	416.93	767.58	201.10
Parkers Cove	0.133	12	2.04	1.12	40.34	17.82	59.77	15.53
Stratified estimates	1.000	92	25.55	5.10	908.83	111.87	581.33	87.42
< 90 m		67	12.86	3.82	797.12	129.11	615.78	110.53
≥ 90 m		25	31.17	10.54	891.52	120.13	282.86	41.81

Table 8. Average shell height (mm) by year-class for scallops from monitoring surveys of Scallop Production Area 4 from 2000 to 2001. Expected shell heights-at-age t for June 2001 were predicted from equation in Fig. 10 and shell height-at-age $t-1$ from June 2000.

	Shell height (mm)							
	2000			June 2001	2001			
Year-class	June	Oct.	Dec.	Expected	May	June	Aug.	Nov.
2000					32.07	37.28	40.58	50.86
1999	31.55	35.00	31.40	53.82	59.62	50.53	56.80	64.36
1998	45.63	55.57	59.90	65.07	74.36	74.81	79.04	84.69
1997	68.46	71.54	76.84	83.31	93.97	94.63	99.30	97.96
1996	85.11	88.38	93.73	96.61	109.08	105.87	110.21	109.96
1995	98.61	100.90	106.32	107.40	117.89	113.25	117.70	118.47
1994	108.98	110.07	115.29	115.68	125.90	118.71	126.10	122.79
1993	116.57	117.82	121.72	121.75	126.20	122.05	126.67	125.75
1992	121.50	121.67	123.88	125.69		121.38	132.50	130.00
1991	122.11		125.70	126.18		128.00		
1990	128.80		132.00	131.52			138.00	140.00
1989	126.00		131.67	129.28				
1988	139.00		139.33					

Table 9. Average shell height-at-age (mm) for scallops from samples taken during June 1990 research survey of Digby area.

	Year-class				
Age	1983	1984	1985	1986	1987
2	54.40	54.45	56.09	57.30	54.98
3	69.67	74.65	79.00	80.82	81.48
4	86.00	90.55	94.99	98.61	
5	98.83	102.77	106.69		
6	108.33	112.03			
7	113.33				

Table 10. Average meat weight (g) at age for scallops from monitoring surveys of Scallop Production Area 4 from 2000 to 2001. Expected meat weight-at-age t for June 2001 were predicted from equation in Fig. 11 and meat weight-at-age $t-1$ from June 2000.

	Meat weight (g)							
	2000			June 2001	2001			
Year-class	June	Oct.	Dec.	Expected	May	June	Aug.	Nov.
2000			0.08		0.39	0.63	0.76	1.61
1999	0.29	0.51	0.31		2.44	1.69	2.24	3.01
1998	0.97	2.26	2.76	4.07	4.78	5.32	5.67	7.63
1997	3.50	5.18	6.32	6.45	10.76	11.26	11.69	11.34
1996	6.91	10.19	12.01	9.67	17.01	15.73	15.55	17.32
1995	11.21	13.99	17.64	13.72	22.66	19.99	19.06	22.02
1994	16.56	16.98	22.74	18.77	25.61	24.62	26.06	25.41
1993	20.59	23.56	28.67	22.50	26.58	27.70	25.12	26.35
1992	23.92	20.35	28.43	25.71		26.01	30.15	27.76

Table 11. Average meat weight (g) at shell height for scallops from annual dredge surveys of Scallop Production Area (SPA) 4 from 1996 to the present.

Shell	Meat weight (g)					
Height (mm)	1996	1997	1998	1999	2000	2001
40	0.8	0.8	0.7	0.9	0.7	0.8
45	1.2	1.2	1.1	1.3	1.0	1.2
50	1.6	1.6	1.5	1.8	1.4	1.6
55	2.1	2.1	2.0	2.3	1.9	2.2
60	2.7	2.7	2.5	3.0	2.5	2.8
65	3.5	3.4	3.2	3.8	3.2	3.6
70	4.3	4.2	4.0	4.7	4.1	4.6
75	5.3	5.2	5.0	5.8	5.1	5.6
80	6.4	6.2	6.1	7.0	6.3	6.9
85	7.6	7.4	7.3	8.3	7.6	8.3
90	9.0	8.7	8.7	9.9	9.1	9.9
95	10.6	10.2	10.2	11.6	10.8	11.7
100	12.3	11.8	11.9	13.4	12.7	13.7
105	14.2	13.6	13.8	15.5	14.8	15.9
110	16.3	15.6	15.9	17.8	17.2	18.4
115	18.5	17.7	18.2	20.3	19.7	21.1
120	21.0	20.1	20.7	22.9	22.6	24.0
125	23.7	22.6	23.4	25.9	25.7	27.2
130	26.6	25.3	26.3	29.0	29.1	30.8
135	29.7	28.2	29.5	32.4	32.8	34.5
140	33.0	31.3	32.9	36.1	36.8	38.6
145	36.6	34.7	36.6	40.0	41.1	43.1
150	40.4	38.2	40.6	44.2	45.8	47.8
155	44.5	42.0	44.8	48.6	50.8	52.9
160	48.8	46.1	49.3	53.4	56.2	58.3

Table 12. Average meat weight (g) at shell height for scallops from common stations fished during annual dredge surveys and monitoring surveys by the F.V. Julie-Ann Joan and the J.L. Hart in Scallop Production Area (SPA) 4.

Shell	Meat weight (g)							
	2000			2001				
Height (mm)	June	Oct.	Dec.	Feb.	May	June	Aug.	Nov.
40	0.6	0.8	0.7	0.5	0.7	0.8	0.7	0.6
45	0.9	1.2	1.0	0.8	1.0	1.1	1.0	0.9
50	1.3	1.6	1.4	1.2	1.4	1.5	1.4	1.3
55	1.7	2.2	2.0	1.6	1.8	2.1	1.9	1.8
60	2.3	2.9	2.7	2.2	2.4	2.7	2.4	2.4
65	3.0	3.7	3.5	3.0	3.2	3.5	3.1	3.1
70	3.8	4.6	4.4	3.8	4.0	4.4	3.9	3.9
75	4.7	5.7	5.6	4.9	5.0	5.4	4.9	4.9
80	5.8	7.0	6.9	6.1	6.1	6.6	5.9	6.1
85	7.1	8.4	8.5	7.6	7.5	8.0	7.1	7.4
90	8.5	10.0	10.2	9.3	9.0	9.6	8.5	8.9
95	10.2	11.8	12.3	11.2	10.7	11.4	10.1	10.6
100	12.0	13.9	14.6	13.5	12.6	13.3	11.8	12.6
105	14.1	16.1	17.1	16.0	14.7	15.5	13.7	14.7
110	16.4	18.6	20.0	18.8	17.1	17.9	15.8	17.1
115	18.9	21.4	23.2	22.0	19.8	20.6	18.2	19.8
120	21.8	24.4	26.7	25.6	22.6	23.5	20.7	22.7
125	24.9	27.6	30.6	29.5	25.8	26.7	23.5	26.0
130	28.2	31.2	34.9	33.9	29.3	30.2	26.5	29.5
135	31.9	35.1	39.6	38.7	33.1	34.0	29.8	33.4
140	36.0	39.2	44.7	44.0	37.2	38.1	33.3	37.6
145	40.3	43.7	50.2	49.8	41.6	42.5	37.1	42.1
150	45.0	48.6	56.2	56.1	46.4	47.2	41.2	47.0
155	50.1	53.7	62.7	63.0	51.6	52.3	45.6	52.3
160	55.6	59.3	69.7	70.4	57.1	57.7	50.3	58.0

Table 13. Analysis of variance table for shell height/meat weight model with piecewise relationship for depth. Scallop Production Area (SPA) 4.

Terms	Value	Std. Error	Student's *t* value	*p*-level
Intercept (1996)	−11.020	0.052	−212.238	0.000
1997-1996	0.172	0.072	2.402	0.016
1998-1996	−0.456	0.081	−5.593	0.000
1999-1996	0.080	0.069	1.161	0.246
2000-1996	−1.044	0.059	−17.675	0.000
2001-1996	−0.583	0.074	−7.853	0.000
β_{1996}	2.935	0.011	257.533	0.000
$\beta_{1997} - \beta_{1996}$	−0.045	0.016	−2.861	0.004
$\beta_{1998} - \beta_{1996}$	0.091	0.018	5.158	0.000
$\beta_{1999} - \beta_{1996}$	0.002	0.015	0.105	0.916
$\beta_{2000} - \beta_{1996}$	0.232	0.013	17.722	0.000
$\beta_{2001} - \beta_{1996}$	0.150	0.016	9.108	0.000
$\log(\text{Depth}_{1996} \mid > 90\text{m})$	−0.092	0.003	−34.393	0.000
Difference terms with $\log(\text{Depth}_{1996} \mid > 90\text{m})$:				
$\log(\text{Depth}_{1997} \mid > 90\text{m})$	0.001	0.003	0.416	0.677
$\log(\text{Depth}_{1998} \mid > 90\text{m})$	−0.015	0.004	−3.429	0.001
$\log(\text{Depth}_{1999} \mid > 90\text{m})$	−0.002	0.004	−0.390	0.697
$\log(\text{Depth}_{2000} \mid > 90\text{m})$	0.045	0.004	12.048	0.000
$\log(\text{Depth}_{2001} \mid > 90\text{m})$	0.023	0.005	4.495	0.000

Table 14. Data used to fit Catch-Survey Analysis model for Scallop Production Area (SPA) 4.

	Fully recruited		Recruits	Catch	
Year	Numbers ($\times 10^6$)	Average Weight (g)	Numbers ($\times 10^6$)	Weight (t)	Numbers ($\times 10^6$)
1981	36.9	17.7	5.2	553.7	31.3
1982	22.8	16.2	3.0	602.6	37.3
1983	24.4	16.3	2.8	394.6	24.2
1984	18.1	17.5	1.7	350.1	20.0
1985	14.6	17.7	1.3	190.8	10.8
1986	15.7	15.5	3.1	66.5	4.3
1987	28.2	11.7	130.6	1208.6	103.0
1988	196.7	9.4	108.1	2835.2	300.5
1989	102.7	11.1	17.0	347.8	31.4
1990	40.5	13.5	4.5	679.2	50.5
1991	23.9	15.4	0.8	373.4	24.3
1992	15.3	16.3	1.8	285.7	17.6
1993	14.3	17.7	0.9	230.8	13.0
1994	9.4	17.0	1.5	209.2	12.3
1995	10.6	16.6	1.9	66.0	4.0
1996	11.8	15.1	5.3	60.8	4.0
1997	16.2	14.1	1.9	116.1	8.2
1998	17.0	13.2	0.6	106.8	8.1
1999	9.4	19.2	0.8	76.7	4.0
2000	10.3	16.9	11.2	102.0	6.0
2001	62.7	10.5	101.0	300.0	28.6

Table 15. Estimated population numbers of fully recruited scallops (millions) from the Catch-Survey Analysis model for Scallop Production Area (SPA) 4. The column labelled Last Year are results from Smith and Lundy (2000) for 1991–2000. The column labelled This Year is for the same years but using the new data presented in this report. Natural mortality was set to 0.10 for the constant M results. Natural mortality set to mortality estimates in Fig. 17 for $S = 231/365$. The catchability of fully-recruited scallops and recruits to the survey gear are denoted as q_I and q_R, respectively.

	$q_n = q_R$, Constant M				$q_I = 1.43q_R$, Constant M	$q_I = 1.43q_R$, Variable M
Year	Last Year	This Year	1991–2001	1981–2001	1981–2001	1981–2001
1981				132.824	106.914	201.859
1982				106.576	87.076	173.076
1983				85.794	68.498	148.996
1984				71.651	57.276	126.094
1985				59.721	46.611	109.552
1986				59.964	46.003	110.330
1987				80.347	64.249	157.871
1988				485.440	415.052	1290.215
1989				324.212	269.804	1054.137
1990				183.901	152.468	204.750
1991	86.375	131.295	163.311	102.687	83.558	124.948
1992	61.338	95.516	120.839	66.578	53.017	96.955
1993	50.105	80.468	102.570	53.052	42.250	87.176
1994	39.530	63.796	81.550	41.121	32.106	70.953
1995	35.679	60.379	78.239	37.050	28.298	67.490
1996	32.520	66.599	85.844	41.461	32.342	74.430
1997	39.266	90.486	116.240	57.942	47.616	106.304
1998	41.832	85.393	111.445	54.990	44.354	99.612
1999	34.698	63.890	86.569	41.949	32.621	75.767
2000	30.488	59.396	87.944	42.155	31.828	75.608
2001			286.742	139.464	121.715	286.795
$\widehat{q}_I$	0.2705	0.1706	0.1336	0.27043	0.3407	0.1520

Table 16. Data used to fit Delay-difference model for Scallop Production Area (SPA) 4.

	Fully recruited				
Year	Biomass (t)	Average Weight (g)	Recruits Biomass (t)	Clapper No.s ($\times 10^6$)	Catch Weight (t)
1981	652	17.7	43.99	1.15	553.7
1982	368	16.2	25.81	0.66	602.6
1983	398	16.3	24.05	0.82	394.6
1984	317	17.5	14.05	0.83	350.1
1985	258	17.7	10.96	0.46	190.8
1986	243	15.5	26.35	0.65	66.5
1987	330	11.7	1110.38	0.99	1208.6
1988	1856	9.4	919.02	2.02	2835.2
1989	1137	11.1	144.80	51.67	347.8
1990	545	13.5	37.96	81.20	679.2
1991	367	15.4	6.82	11.50	373.4
1992	249	16.3	15.27	1.61	285.7
1993	253	17.7	7.95	0.71	230.8
1994	161	17.0	12.44	0.42	209.2
1995	176	16.6	16.55	0.86	66.0
1996	178	15.1	44.86	0.85	60.8
1997	229	14.1	15.86	0.62	116.1
1998	225	13.2	4.79	0.89	106.8
1999	180	19.2	6.38	0.62	76.7
2000	175	16.9	95.37	0.94	102.0
2001	661	10.5	858.85	1.94	400.0

Table 17. Summary of posterior distributions for model parameters. The column labelled SD corresponds to a naïve estimator of the standard deviation — assumes no autocorrelation. The columns labelled 0.025 and 0.975 refer to the lower and upper limits of the credible regions for the posterior distribution of the parameter.

Node	Mean	SD	0.025	Median	0.975
K	3486.0	2756.0	1401.0	2646.0	12380
σ^2	0.0868	0.0334	0.0418	0.0802	0.1705
σ^2_ε	0.0543	0.0175	0.0298	0.0510	0.0975
σ^2_ν	0.3291	0.1750	0.1202	0.2908	0.7694
σ^2_ϵ	0.3215	0.1629	0.1223	0.2862	0.7319
σ^2_φ	0.0542	0.0178	0.0297	0.0509	0.0973
q_I	0.2261	0.0951	0.0434	0.2279	0.4081
q_R	0.0953	0.0399	0.0221	0.0941	0.1792
S	0.5996	0.1470	0.3487	0.5846	0.9119

Table 18. Estimates from the Delay-difference model with 95 percent credible regions for Scallop Production Area (SPA) 4.

	Biomass (t)			Recruits (t)			Mortality		
Season	0.025	0.50	0.975	0.025	0.50	0.975	0.025	0.50	0.975
1980-1981	1421	2579	13270	128	408	1942	0.02	0.06	0.20
1981-1982	1003	1833	9112	97	317	1498	0.02	0.05	0.20
1982-1983	866	1676	9028	82	267	1299	0.02	0.07	0.20
1983-1984	743	1399	7366	54	175	831	0.03	0.08	0.27
1984-1985	594	1164	6210	43	142	706	0.02	0.06	0.20
1985-1986	548	1098	5905	95	313	1554	0.03	0.08	0.25
1986-1987	737	1447	7647	3859	7866	35100	0.03	0.08	0.22
1987-1988	4127	7869	41510	1589	5598	26090	0.01	0.03	0.10
1988-1989	2672	5279	28480	380	1395	7531	0.23	0.66	1.41
1989-1990	1313	2418	12530	131	435	2184	0.60	1.19	1.89
1990-1991	843	1552	8177	28	94	485	0.18	0.49	1.03
1991-1992	591	1130	5982	59	193	892	0.05	0.16	0.47
1992-1993	545	1044	5589	31	102	497	0.03	0.09	0.28
1993-1994	402	777	4049	51	169	823	0.03	0.08	0.27
1994-1995	377	744	4142	61	193	986	0.05	0.14	0.39
1995-1996	402	785	4211	127	415	2019	0.05	0.13	0.38
1996-1997	530	1019	5284	57	184	922	0.03	0.08	0.26
1997-1998	510	981	5288	20	67	359	0.03	0.10	0.32
1998-1999	426	845	4448	26	91	459	0.03	0.10	0.34
1999-2000	404	804	4293	532	1471	6648	0.05	0.16	0.43
2000-2001	1400	2685	13870	1546	6256	28810	0.03	0.07	0.20

Table 19. Estimates from the CSA model with 95 percent bootstrap confidence intervals for Scallop Production Area (SPA) 4.

	Fully-recruited (millions)			Recruits (millions)		
Year	0.025	Mean	0.975	0.025	Mean	0.975
1981	233.234	272.986	335.855	45.273	53.815	67.814
1982	195.710	231.516	290.635	21.510	25.676	32.788
1983	160.774	197.857	260.278	27.574	32.852	41.298
1984	134.060	167.367	220.463	8.829	10.599	13.342
1985	108.997	138.429	185.079	6.451	7.750	9.776
1986	93.276	125.517	171.353	320.513	384.314	489.328
1987	268.030	338.151	446.105	1419.127	1665.901	2123.365
1988	1444.053	1753.955	2264.048	1156.813	1364.700	1703.369
1989	1046.484	1246.518	1564.422	130.459	154.215	197.843
1990	278.941	316.204	374.809	11.731	14.099	18.133
1991	152.872	179.727	222.353	4.691	5.609	7.162
1992	112.616	134.673	171.107	12.125	14.313	18.236
1993	96.735	119.260	155.031	5.187	6.146	7.867
1994	78.754	98.054	128.887	9.621	11.429	14.452
1995	73.818	93.476	124.995	9.034	10.597	13.426
1996	77.665	98.235	130.843	33.523	39.593	49.778
1997	113.007	136.257	174.819	2.817	3.352	4.295
1998	102.464	125.386	164.498	2.638	3.162	3.982
1999	75.130	96.239	130.770	9.440	11.188	14.227
2000	70.699	91.606	128.375	223.056	268.138	337.015
2001	334.003	423.917	559.774	873.903	1025.924	1282.535

Table 20. Percentage of clappers caught during the monitoring surveys. Above Digby Gut corresponds to the Digby Gut, DG-DC and Delaps Cove strata (see Fig. 7). Below Digby Gut corresponds to the GH-DG and Gullivers Head strata.

Date	Below Digby Gut	Above Digby Gut	Total
June, 2000	5.27	6.15	5.72
October, 2000	1.12	0.00	0.75
December, 2000	3.55	0.40	0.86
February, 2001	1.12	0.76	0.93
May, 2001	2.05	0.88	1.08
June, 2001	3.13	2.60	2.78
August, 2001	1.83	1.09	0.77
November, 2001	2.26	0.46	0.46

Table 21. Posterior probabilities of exceeding $F_{0.1} = 0.14$. Natural mortality for 2001/2002 set equal to that estimated for 2000/01 at 0.07. Note current TAC set at 400 t with 243 t landed as of 28/01/2002.

2001/2002			TAC 2002/03, $P(F > F_{0.1})$					
Catch(t)	$\widehat{F}$	$P(F > F_{0.1})$	500	600	700	800	900	1000
300	0.12	0.35	0.04	0.10	0.17	0.25	0.33	0.40
350	0.14	0.50	0.05	0.11	0.18	0.25	0.34	0.41
400	0.17	0.61	0.05	0.11	0.18	0.26	0.34	0.42
450	0.19	0.69	0.06	0.12	0.19	0.27	0.35	0.42
500	0.21	0.75	0.06	0.12	0.19	0.27	0.35	0.43
600	0.26	0.82	0.07	0.13	0.20	0.29	0.37	0.44
700	0.32	0.86	0.08	0.14	0.22	0.30	0.38	0.44
800	0.38	0.89	0.09	0.16	0.23	0.31	0.39	0.46
900	0.44	0.91	0.09	0.17	0.24	0.32	0.40	0.47
1000	0.52	0.92	0.10	0.17	0.25	0.33	0.41	0.48

Table 22. Posterior probabilities of exceeding $F_{0.1} = 0.14$. Natural mortality set at three times that estimated for 2000/01 at 0.21.

2001/2002	TAC 2002/03, $P(F > F_{0.1})$					
Catch(t)	500	600	700	800	900	1000
300	0.10	0.18	0.27	0.36	0.44	0.52
350	0.11	0.19	0.28	0.37	0.45	0.53
400	0.11	0.19	0.28	0.37	0.45	0.53
450	0.12	0.20	0.29	0.38	0.46	0.54
500	0.12	0.21	0.30	0.39	0.47	0.54
600	0.13	0.22	0.31	0.40	0.48	0.55
700	0.14	0.22	0.32	0.41	0.49	0.56
800	0.15	0.24	0.33	0.42	0.50	0.57
900	0.16	0.25	0.34	0.43	0.51	0.58
1000	0.17	0.26	0.35	0.44	0.52	0.59

Table 23. Evaluation of different catch scenarios for scallops in SPA 4 in the Bay of Fundy for the current season and the the next three seasons. $B_{crit} = 2300$ t.

Catch (meats, t) in 2001/2002	Median Biomass in 2002	$Pr(B_t < B_{crit})$	Year	Catches in 2002/2003–2004/2005					
				1000 t		1500 t		2000 t	
				Median Biomass	$Pr(B_t < B_{crit})$	Median Biomass	$Pr(B_t < B_{crit})$	Median Biomass	$Pr(B_t < B_{crit})$
400	5533.0	0.01	2003	6248.0	0.05	5707.0	0.09	5054.0	0.15
			2004	5999.0	0.13	5017.0	0.23	3659.0	0.36
			2005	5250.0	0.23	3744.0	0.38	1864.0	0.54
600	5045.0	0.06	2003	5618.0	0.12	5070.0	0.17	4446.0	0.25
			2004	5280.0	0.20	4200.0	0.31	2972.0	0.44
			2005	4530.0	0.30	2910.0	0.45	1141.0	0.59
800	4891.0	0.06	2003	5509.0	0.13	4909.0	0.18	4275.0	0.26
			2004	5277.0	0.22	4070.0	0.33	2803.0	0.45
			2005	4515.0	0.31	2770.0	0.46	996.5	0.61

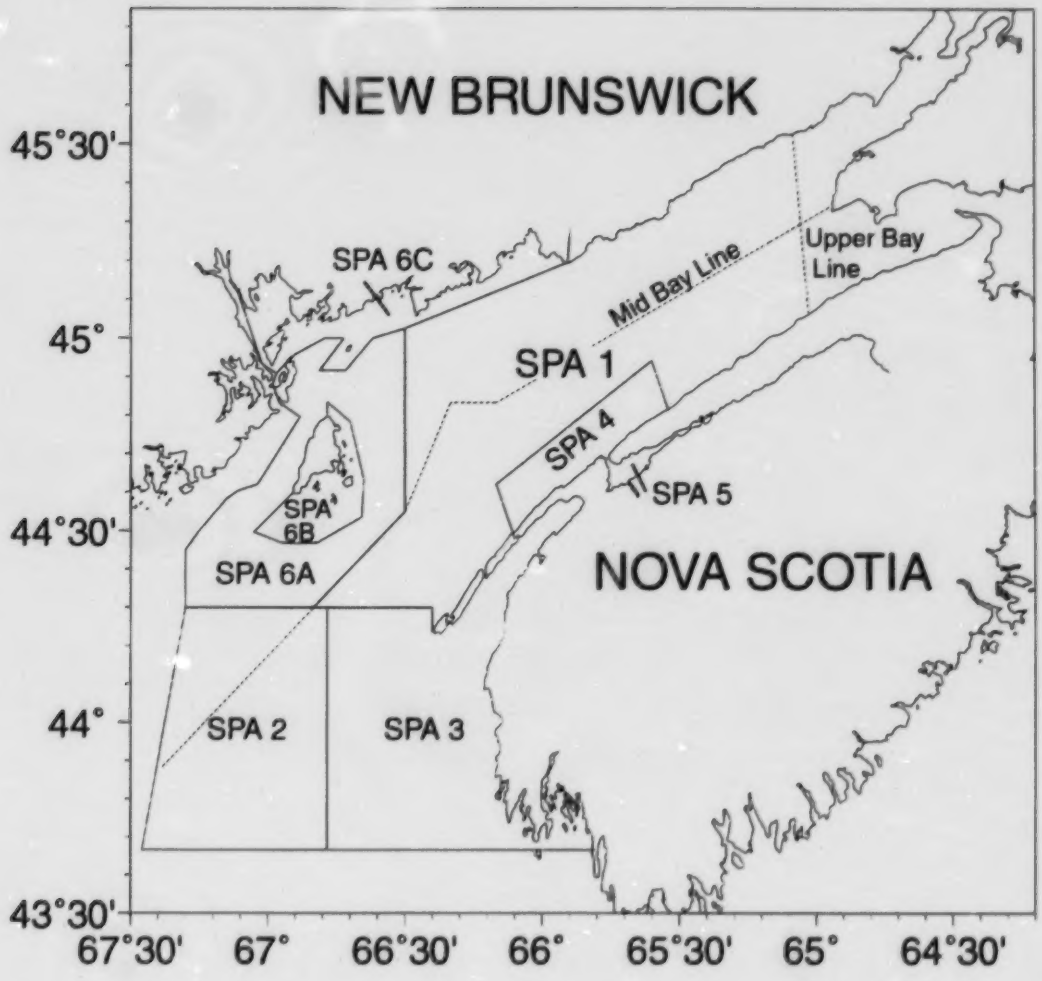

Fig. 1. Scallop Production Areas (SPA) and regulated lines in the Bay of Fundy. The boundaries of the SPA's were established 1 January 1997. In 1999, the number of SPA's was reduced from 7 to 6 (St. Mary's Bay (SPA 7) was combined with Brier Island/Lurcher Shoal (SPA 3)).

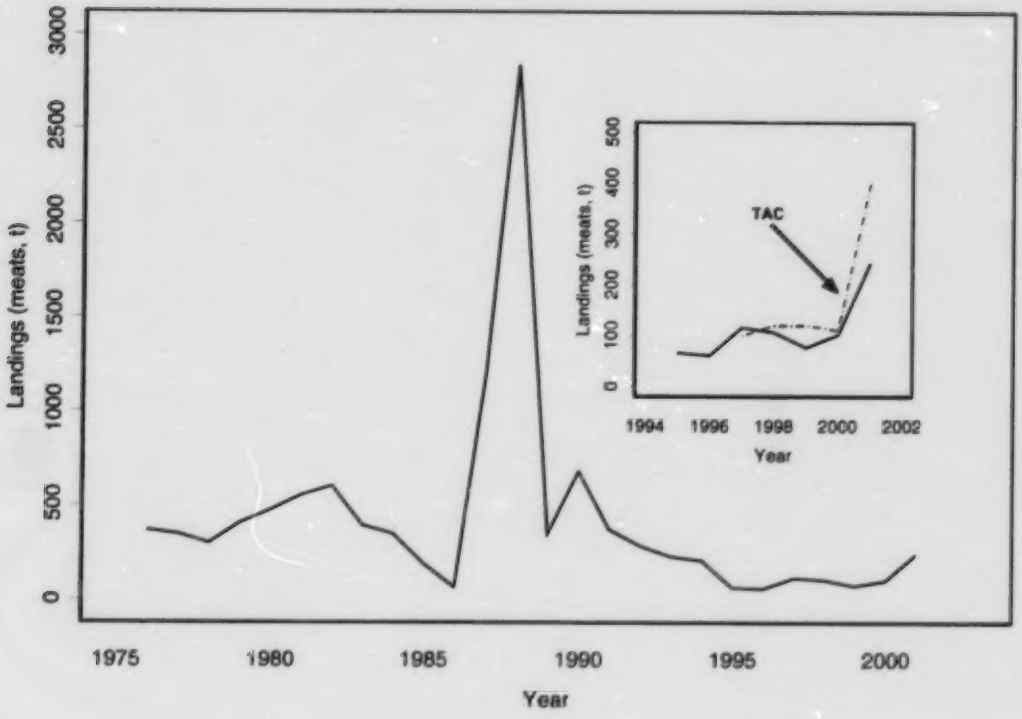

Fig. 2. Scallop landings (meats, t) in Scallop Production Area 4. Total allowable catch (TAC) levels were introduced in 1997. Year indicates the first year of the season, e.g., 1976 refers to landings in the 1976/1977 season. Landings in 2001/2002 season are preliminary as of 28 January 2002.

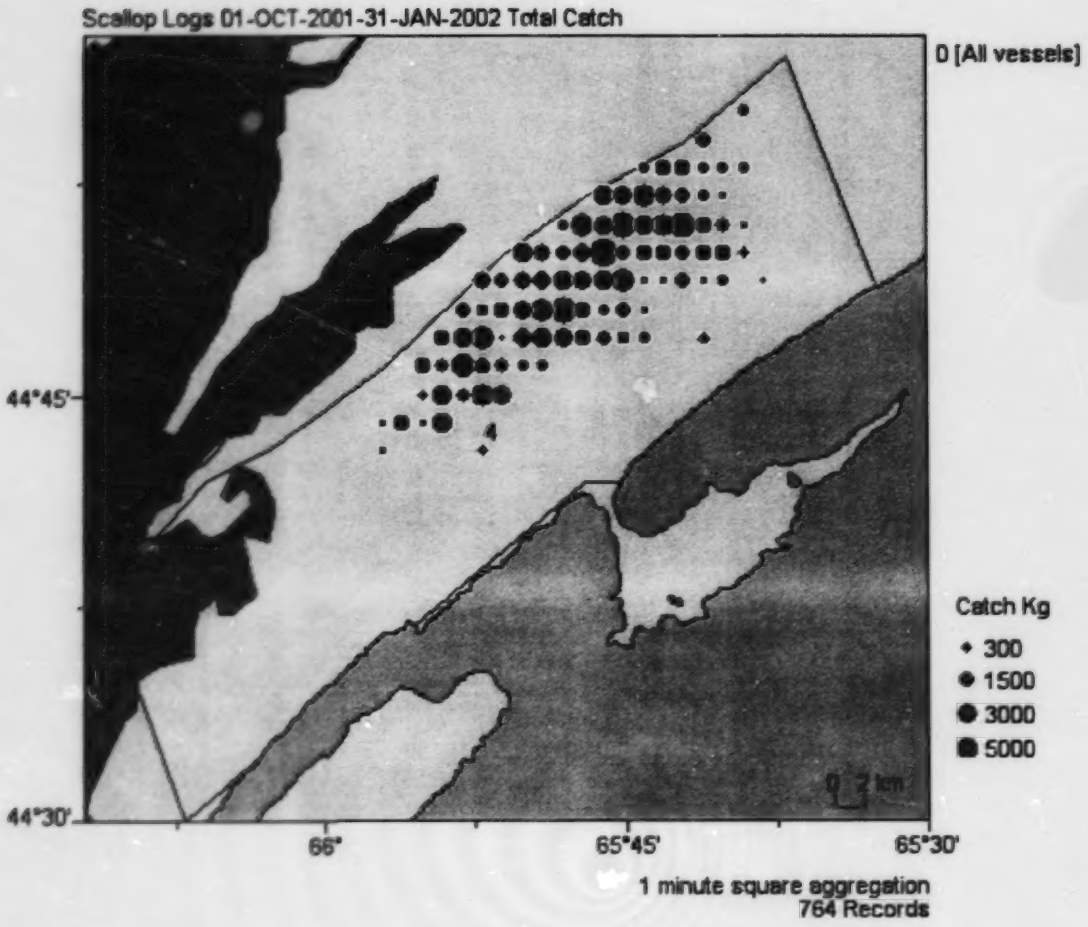

Fig. 3. Positions for scallop landings (meats, t) in Scallop Production Area 4 from commercial log books for 2001/2002 season. Landings are preliminary as of 28 January 2002.

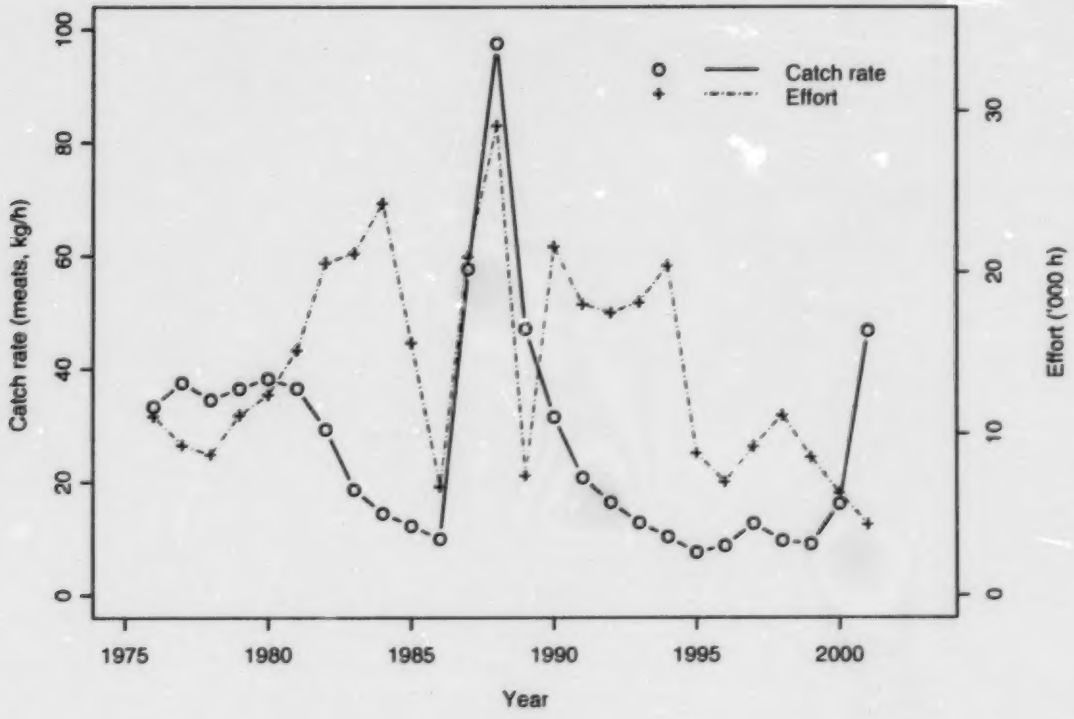

Fig. 4. Commercial catch rate (kg/h) for Full Bay fleet in Scallop Production Area 4. Commercial effort measured in thousands of hours fishing.

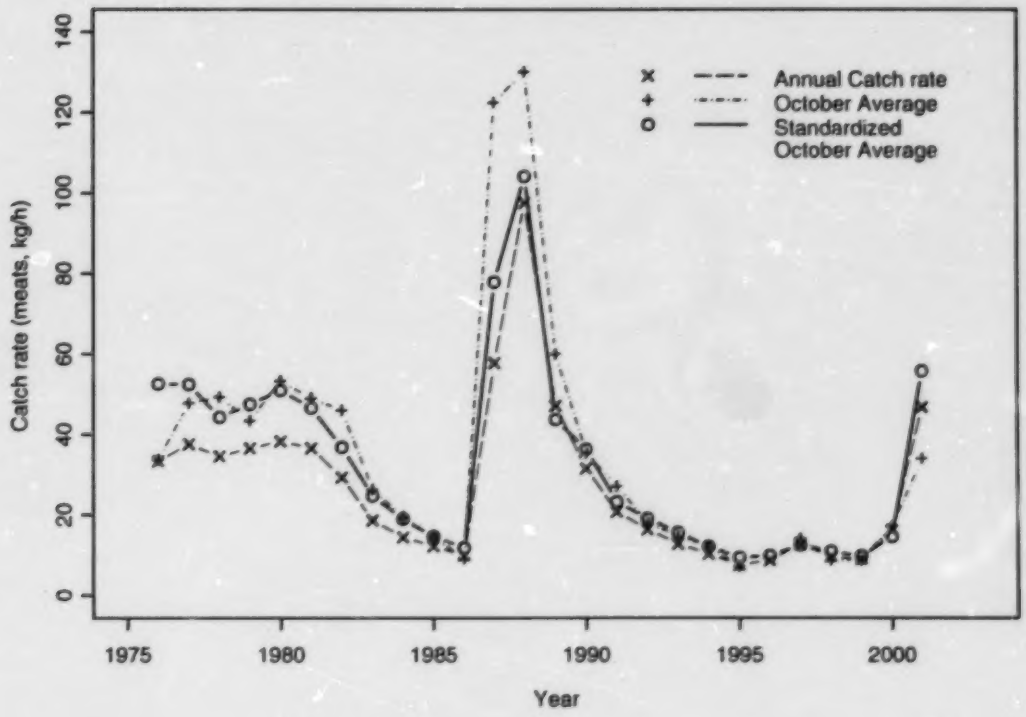

Fig. 5. Commercial catch rate (kg/h) for Full Bay fleet in Scallop Production Area 4. Comparison of trends for annual catch rate, straight average of October catch rates each year and predicted October catch rate from catch rate standardization model (see text).

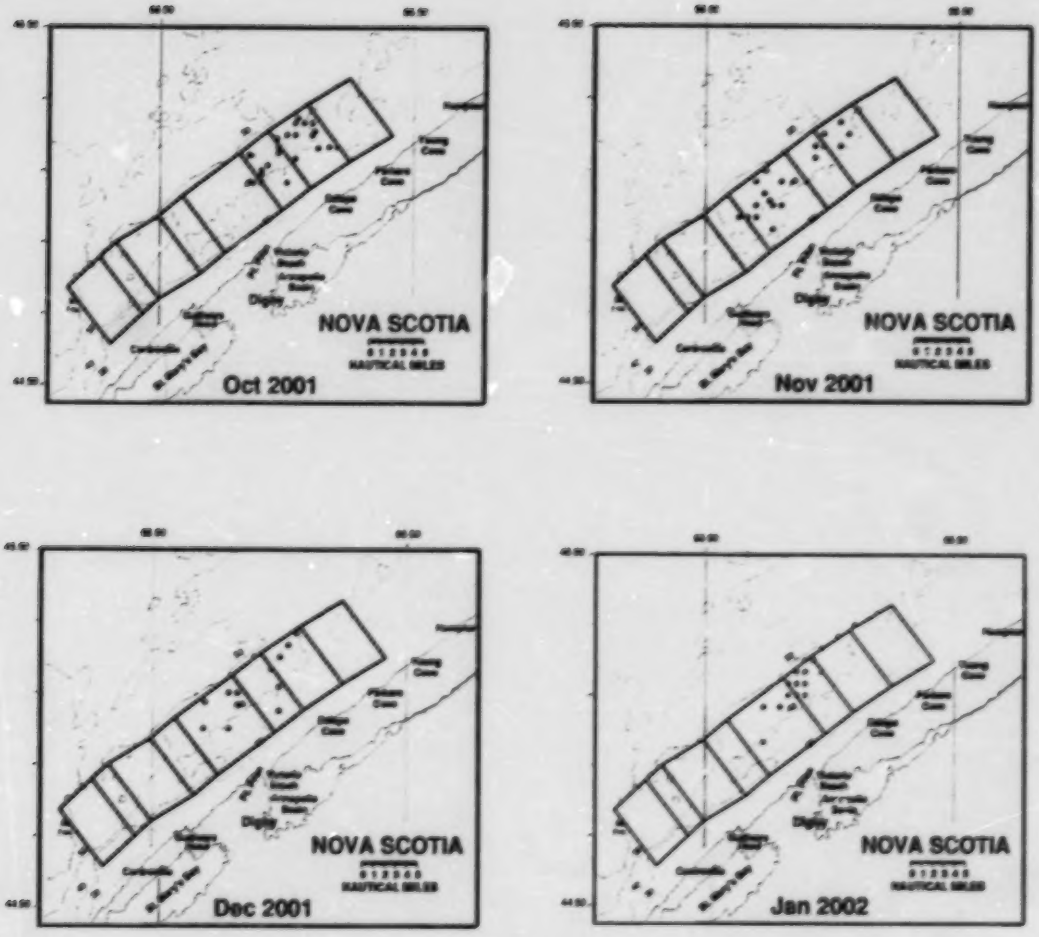

Fig. 6. Reported locations by month of catches sampled for meat weights in the 2001/2002 season for scallops in Scallop Production Area 4. Depths are given in fathoms (1.83 m = 1 fm).

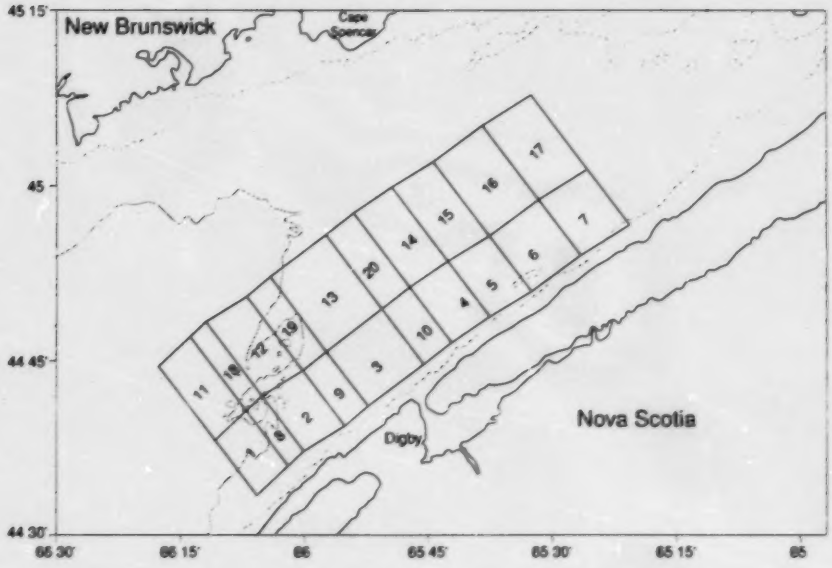

Fig. 7. Location of strata in the Bay of Fundy used for calculation of survey indices for scallops. Strata 1–5 and 8–10 comprise Scallop Production Area 4.

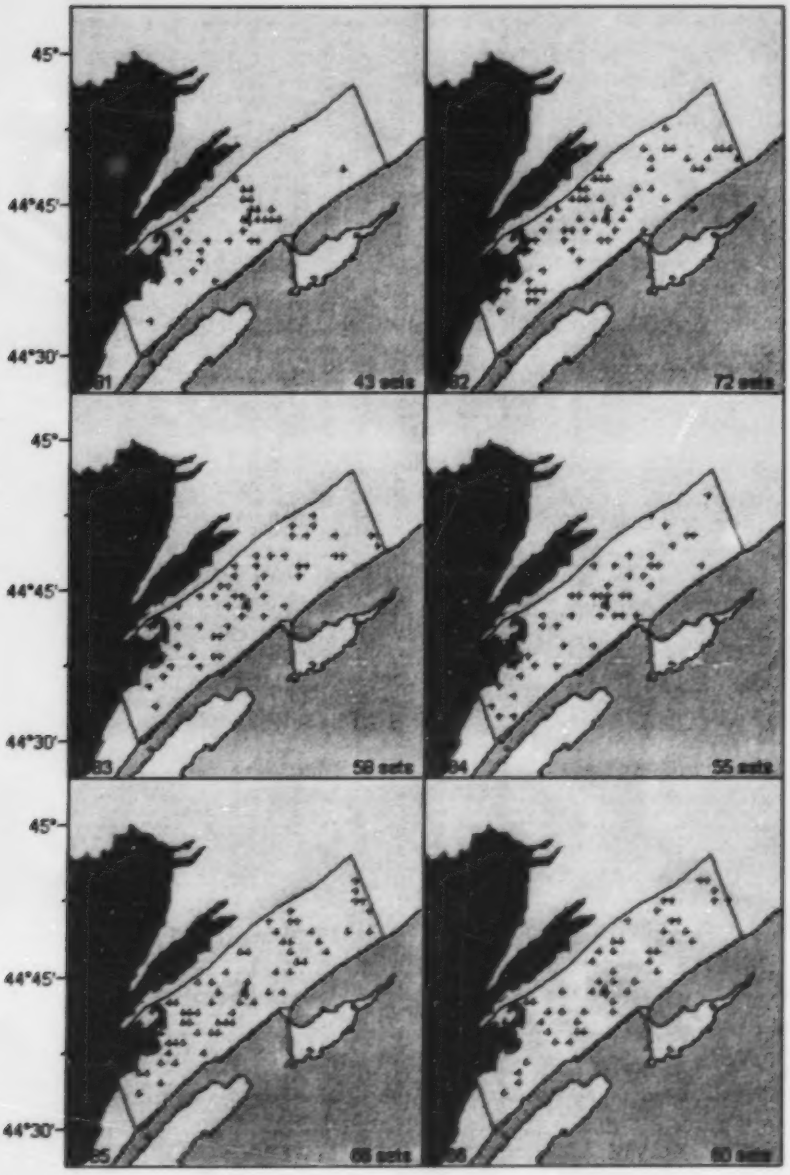

Fig. 8. Locations of tows during annual dredge surveys for scallops in the Bay of Fundy. a) 1981 to 1986. Shaded areas refer to the 100 m depth contour.

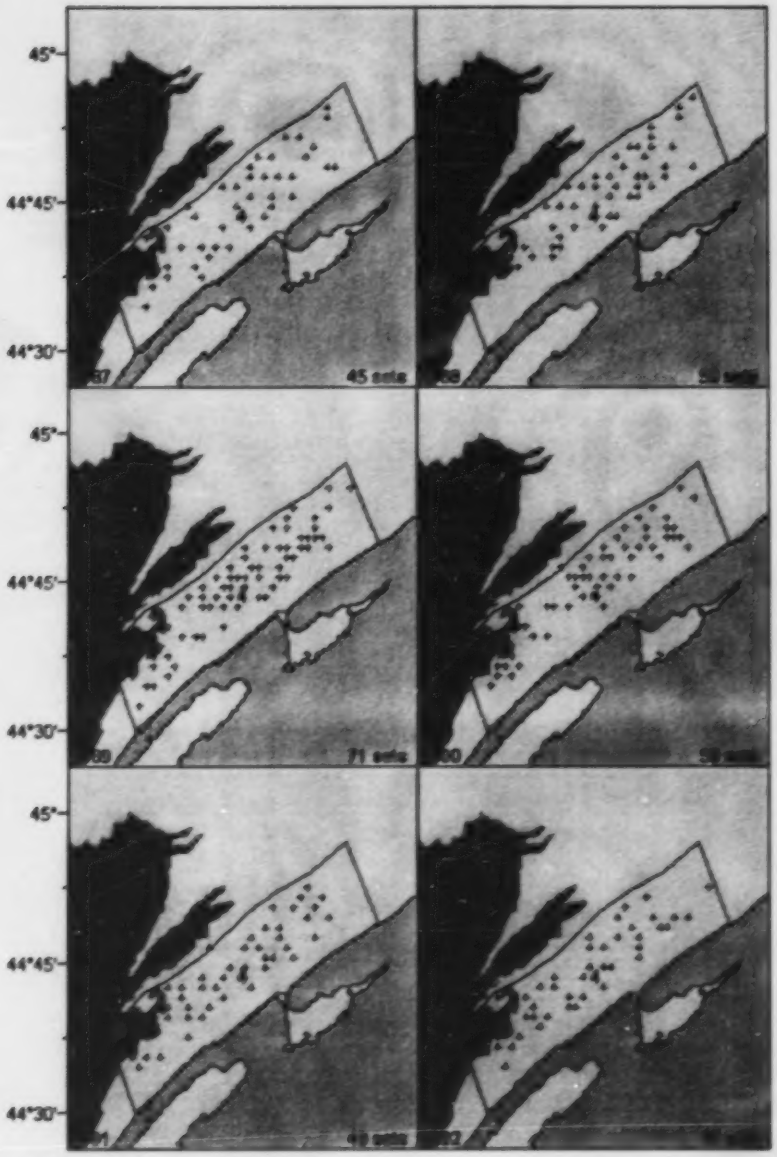

Fig. 8. cont'd. Locations of tows during annual dredge surveys for scallops in the Bay of Fundy. b) 1987 to 1992. Shaded areas refer to the 100 m depth contour.

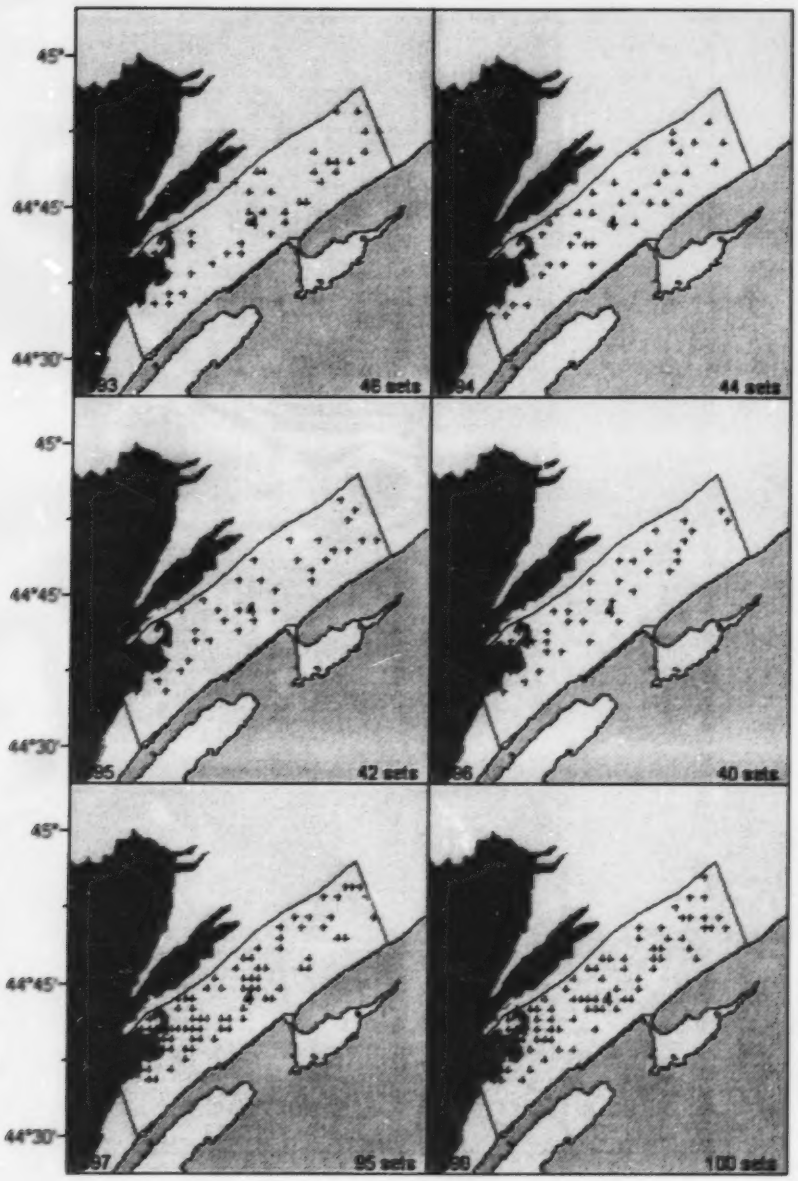

Fig. 8. cont'd. Locations of tows during annual dredge surveys for scallops in the Bay of Fundy. c) 1993 to 1998. Shaded areas refer to the 100 m depth contour.

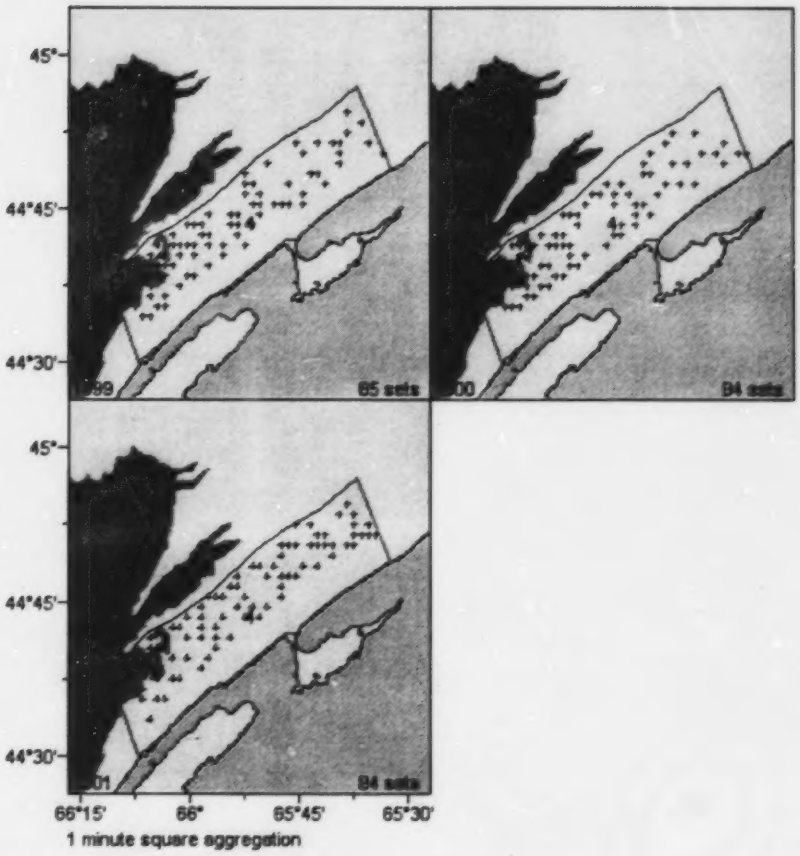

Fig. 8. cont'd. Locations of tows during annual dredge surveys for scallops in the Bay of Fundy. d) 1998 to 2001. Shaded areas refer to the 100 m depth contour.

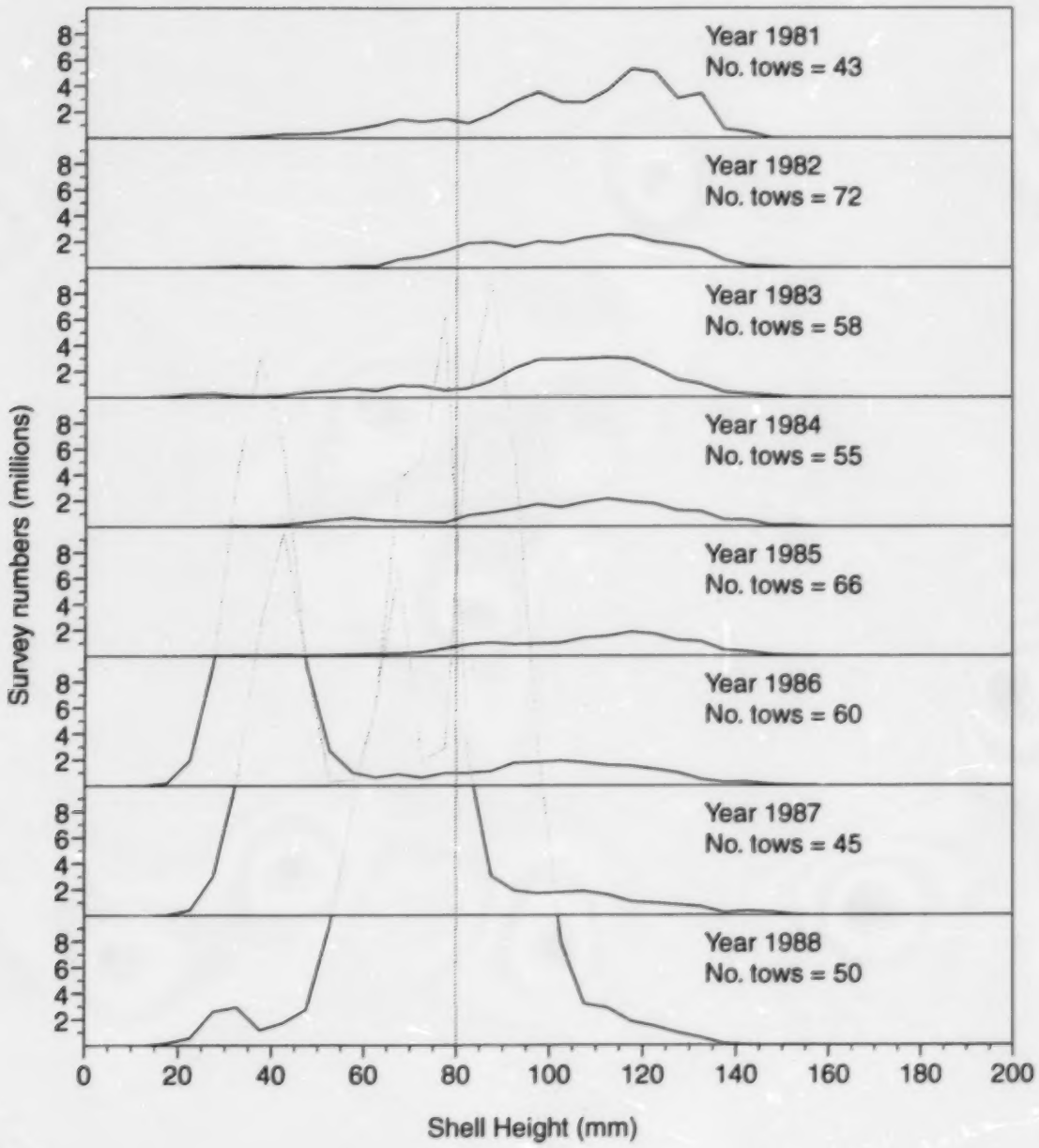

Fig. 9. Shell height frequencies for total numbers from annual scallop dredge surveys in Scallop Production Area 4. a) 1981 to 1988.

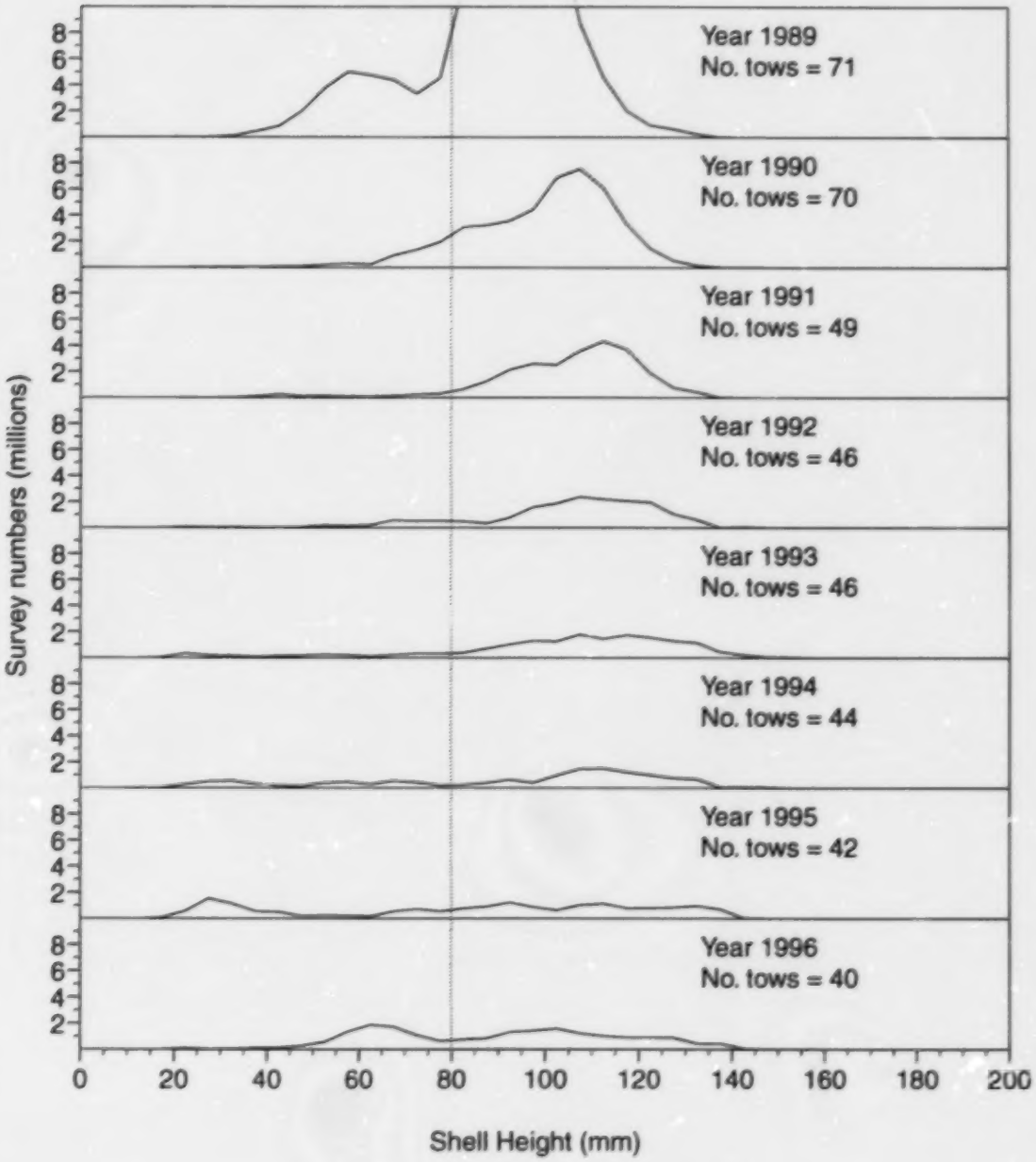

Fig. 9. b) Shell height frequencies 1989 to 1996.

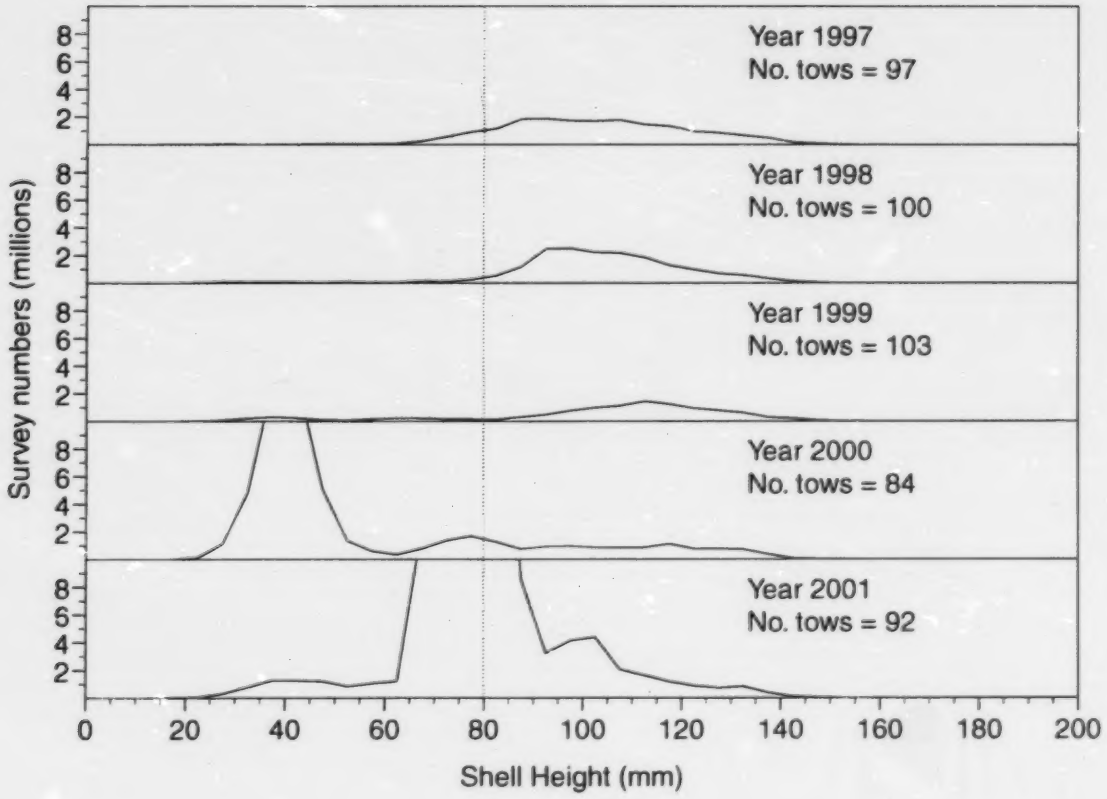

Fig. 9. c) Shell height frequencies 1997 to 2001.

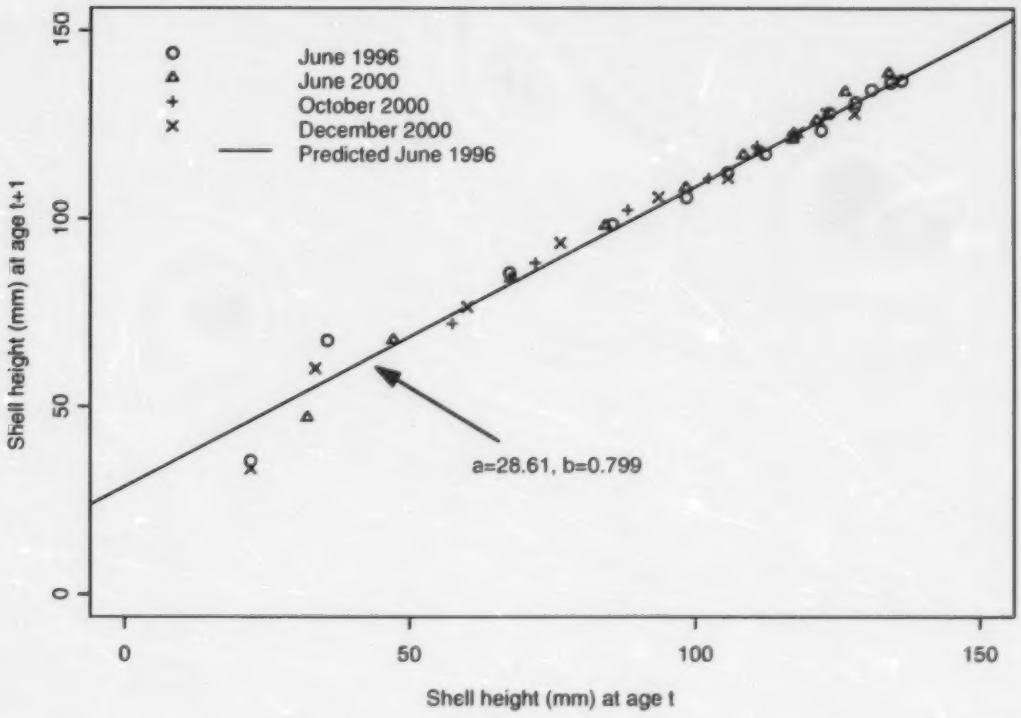

Fig. 10. Relationships between shell heights at age t and $t + 1$ from seasonal surveys in 2000 and from June 1996 survey of Scallop Production Area 4.

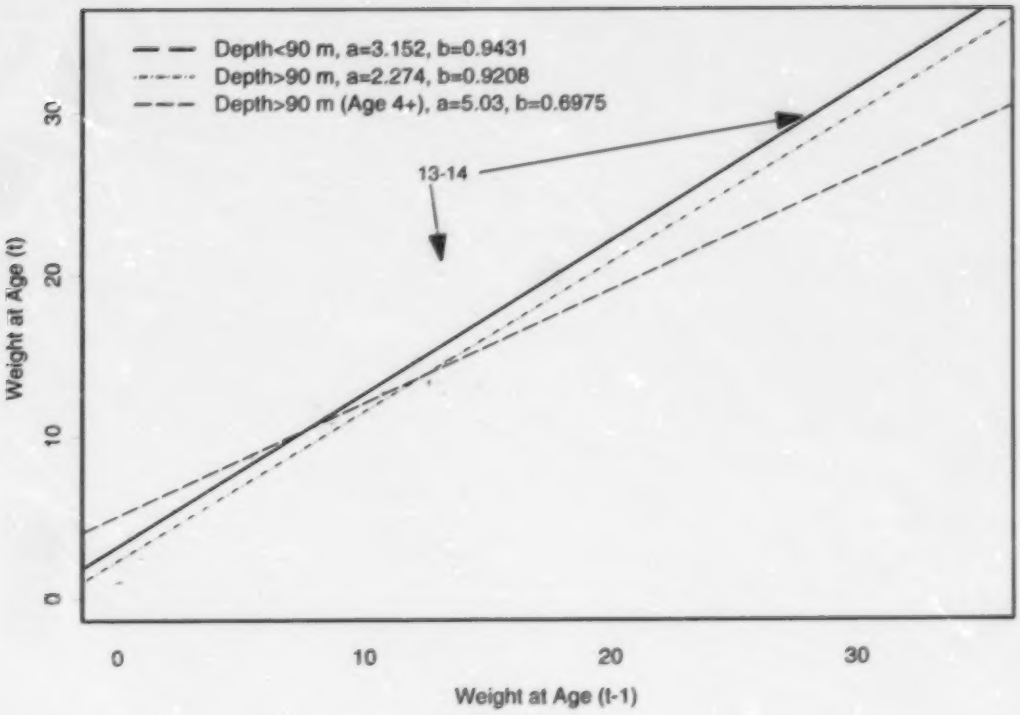

Fig. 11. Weight-age relationships for scallops caught in depths less than and greater than 90 m. Data collected during June 1996 survey from Scallop Production Area 4. Points for transition from age 13 to 14 indicated for both depth ranges.

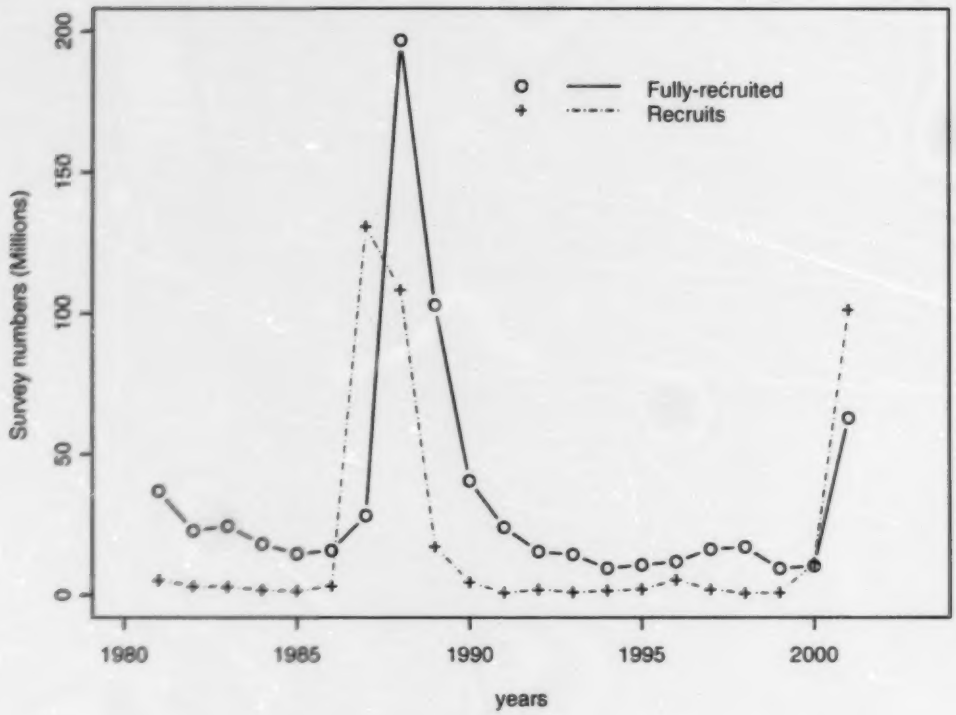

Fig. 12. Trends in survey estimates of total numbers of fully-recruited scallops and recruits (see text for definition) from annual dredge survey of Scallop Production Area 4. Recruits series has not been corrected using fishing efficiency factor from selectivity study (see text).

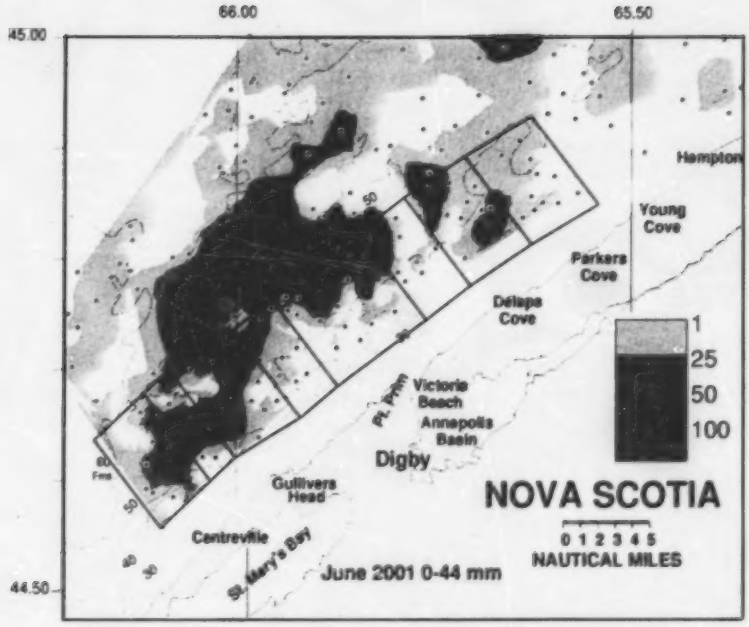

Fig. 13. Spatial distribution of scallop catches from the June 2001 survey of Scallop Production Area 4 for scallops with shell heights between 0 and 45 mm. Contouring was derived using Delauney triangles and inverse distance weight interpolation. Depths are given in fathoms (1.83 m = 1 fm). Tow locations are indicated on the map.

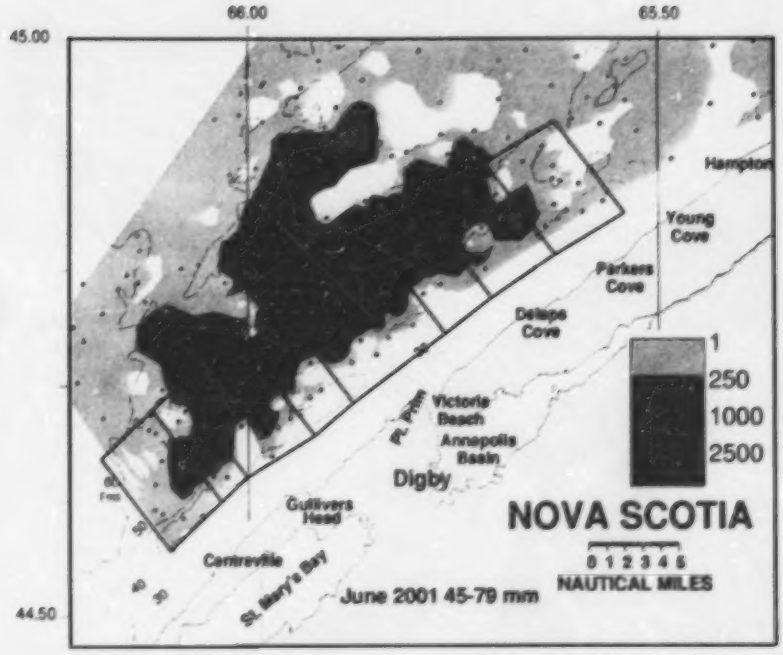

Fig. 14. Spatial distribution of scallop catches from the June 2001 survey of Scallop Production Area 4 for scallops with shell heights between 45 and 80 mm. Contouring was derived using Delauney triangles and inverse distance weight interpolation. Depths are given in fathoms (1.83 m = 1 fm). Tow locations are indicated on the map.

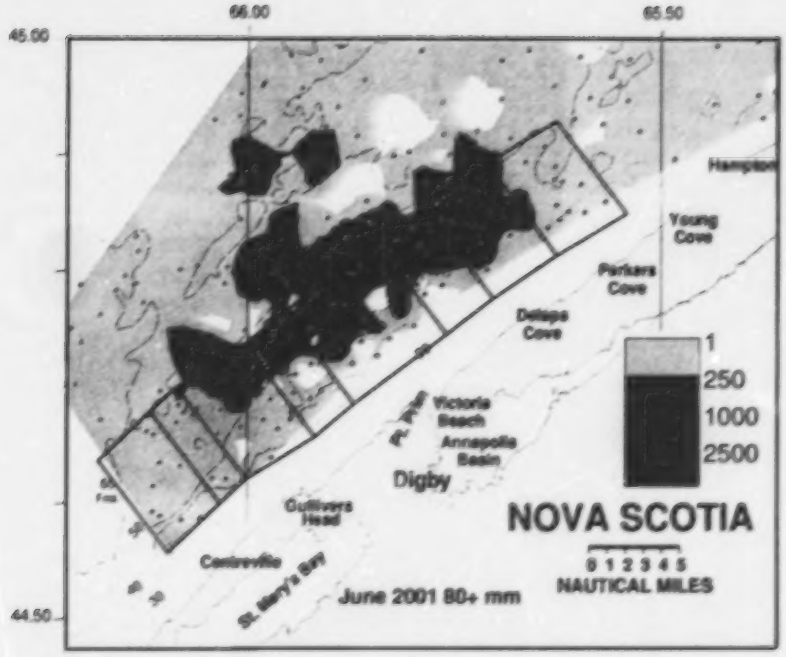

Fig. 15. Spatial distribution of scallop catches from the June 2001 survey of Scallop Production Area 4 for scallops with shell heights greater than 80 mm. Contouring was derived using Delauney triangles and inverse distance weight interpolation. Depths are given in fathoms (1.83 m = 1 fm). Tow locations are indicated on the map.

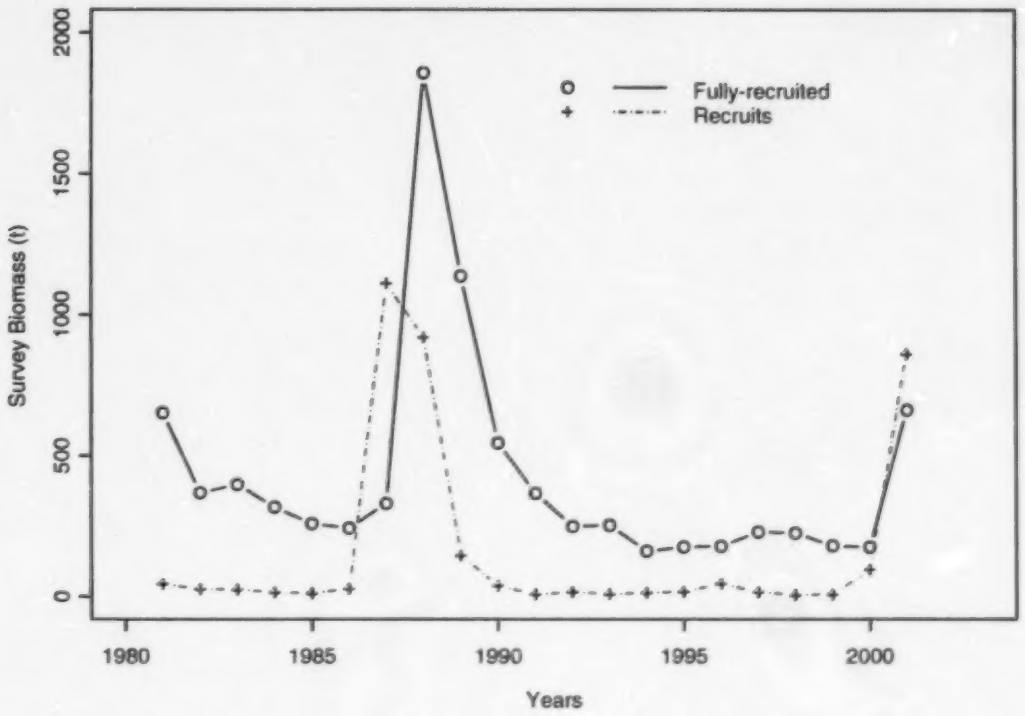

Fig. 16. Trends in survey estimates of biomass (t) of fully-recruited scallops and recruits (see text for definition) from annual dredge survey of Scallop Production Area 4. Recruits series has not been corrected using fishing efficiency factor from selectivity study (see text).

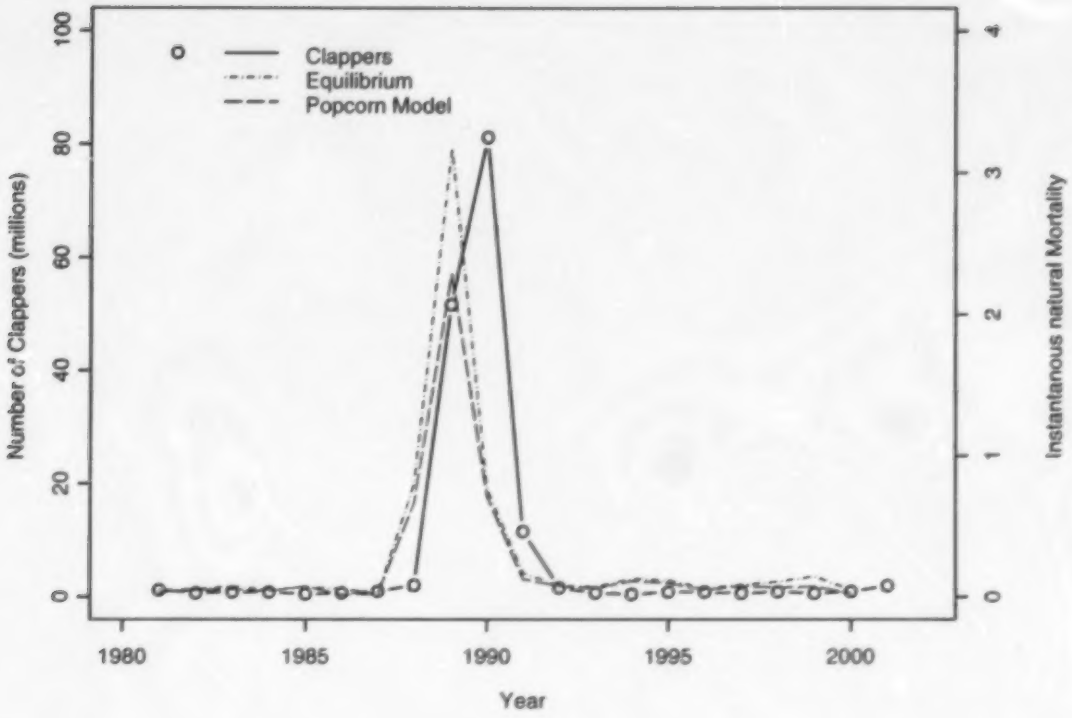

Fig. 17. Trends in natural mortality estimates from the equilibrium and Popcorn models based on the number of clappers observed in the annual dredge survey of Scallop Production Area 4. Mean separation time for clapper hinge was set arbitrarily to be 231 days. Note that clappers observed in year t are assumed to reflect mortality in the previous fishing season. Mortality estimates have been plotted for the year they apply to.

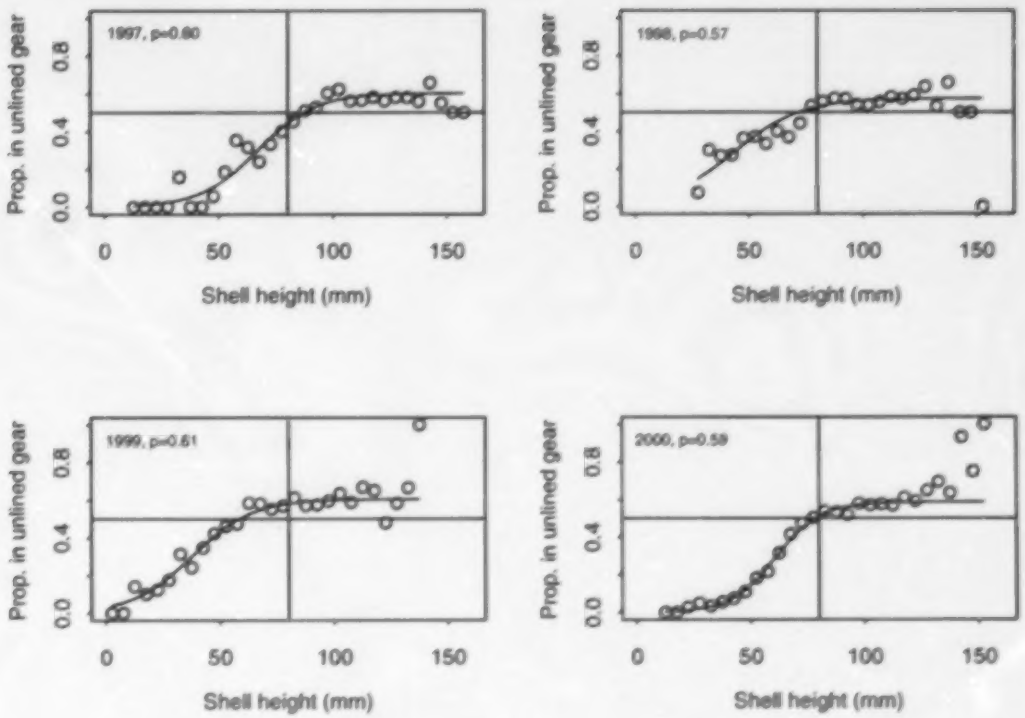

Fig. 18. Results of analysis of relative selectivity of lined versus unlined scallop dredges used in June survey. The relative efficiency of unlined to lined gear is given as p which refers to the probability that a scallop will be retained in the unlined dredge relative to the lined dredge. Selectivity data aggregated over entire survey in each year.

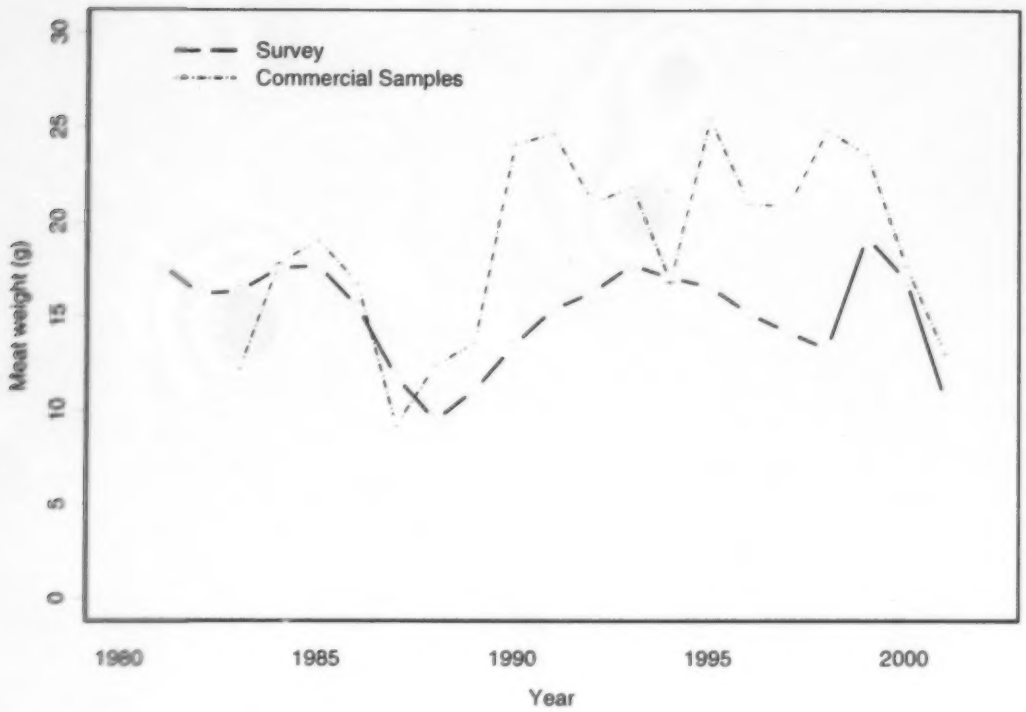

Fig. 19. Trends in average meat weight from fully-recruited scallops in the annual dredge survey of Scallop Production Area 4. Average meat weight from commercial samples estimated from data in Table 5 weighted by catch in Table 1. Estimate for commercial samples for 2001/2002 are preliminary as of 28 January, 2002.

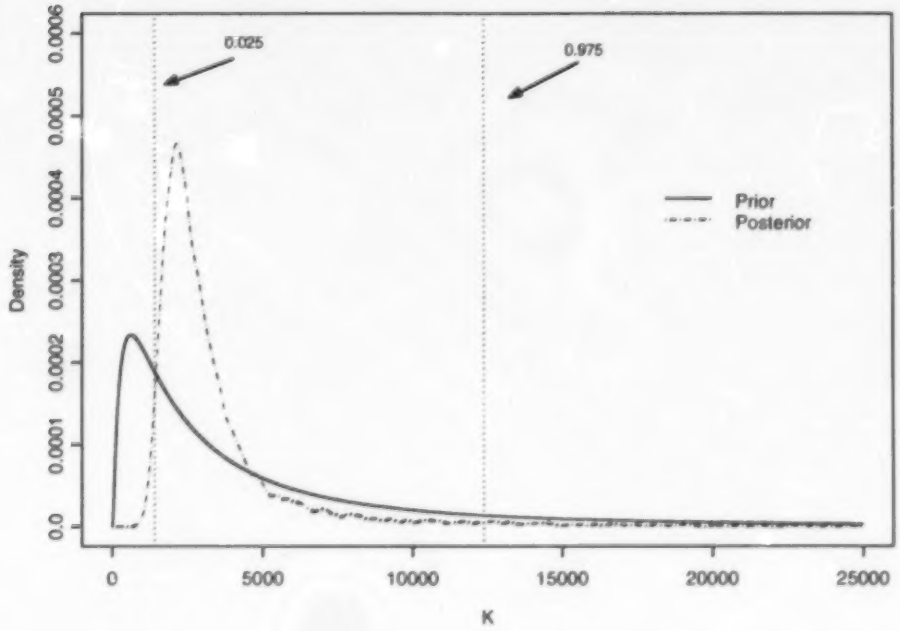

Fig. 20. Relative density functions for prior and posterior distributions for the parameter K.

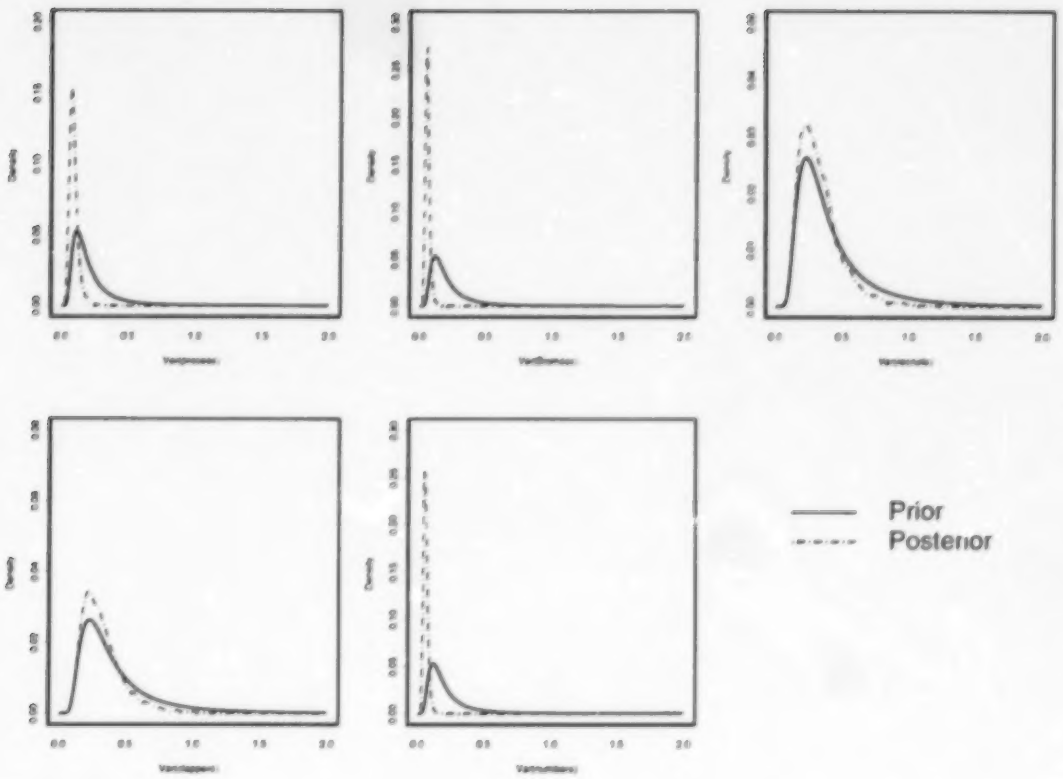

Fig. 21. Relative density functions for prior and posterior distributions for the variance terms in the delay-difference model. Solid line indicates prior and dashed line the posterior.

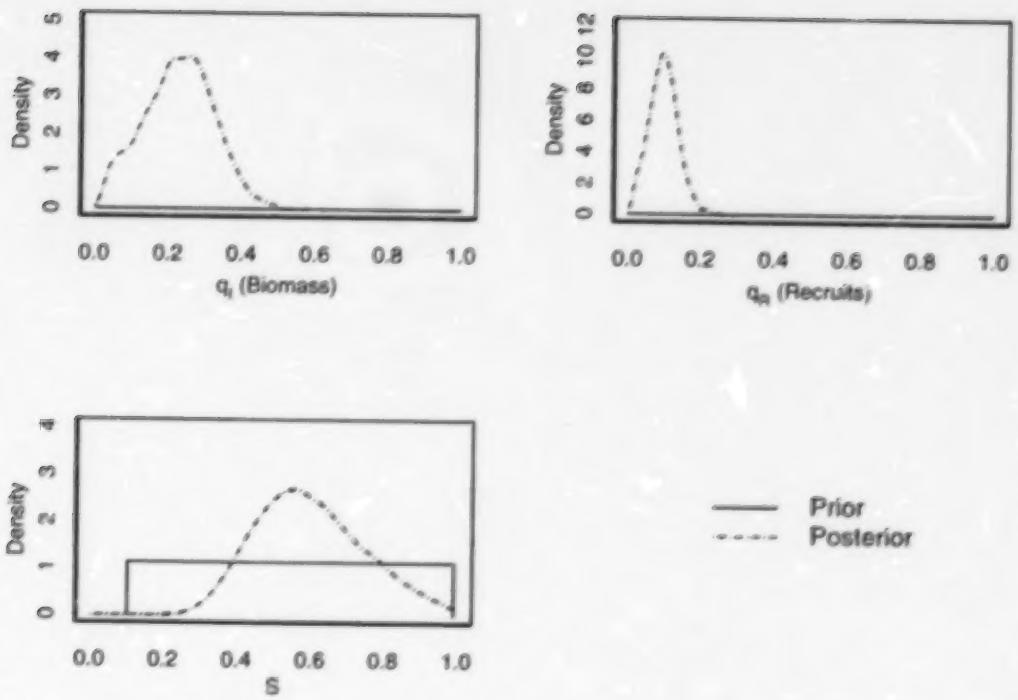

Fig. 22. Relative density functions for posterior distributions for the parameter proportionality constants q_I, q_R and the dissolution rate S.

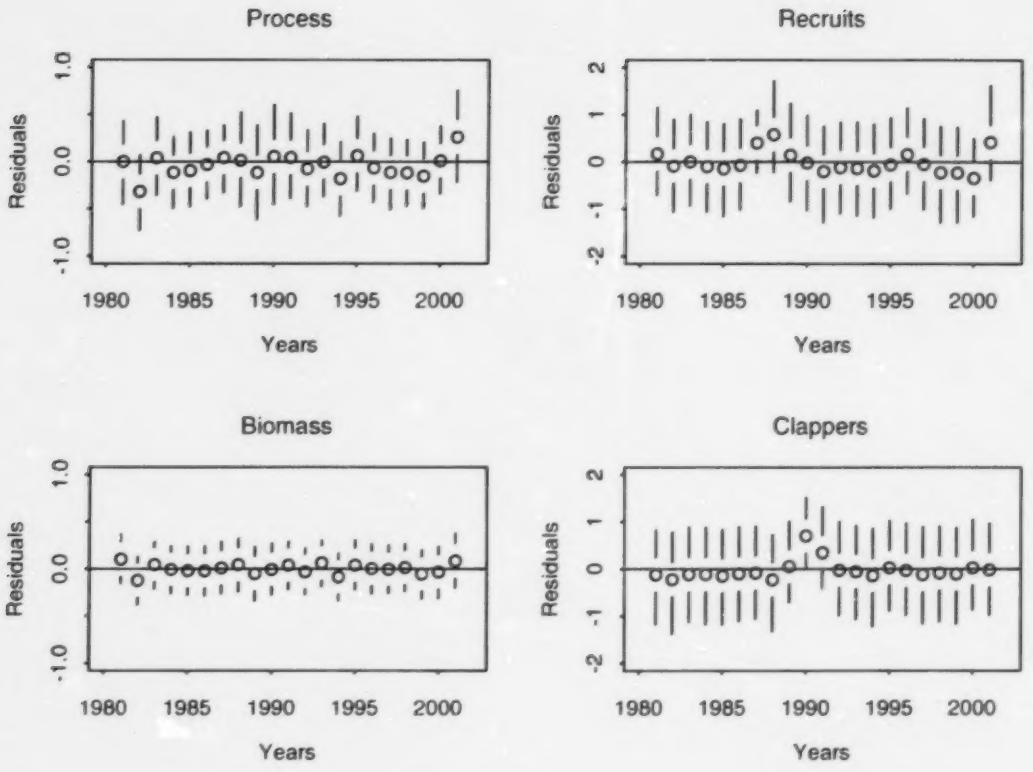

Fig. 23. Residuals for four of the main terms in the likelihood. The lower and upper vertical lines connect to the 0.025 and 0.975 percentiles, respectively.

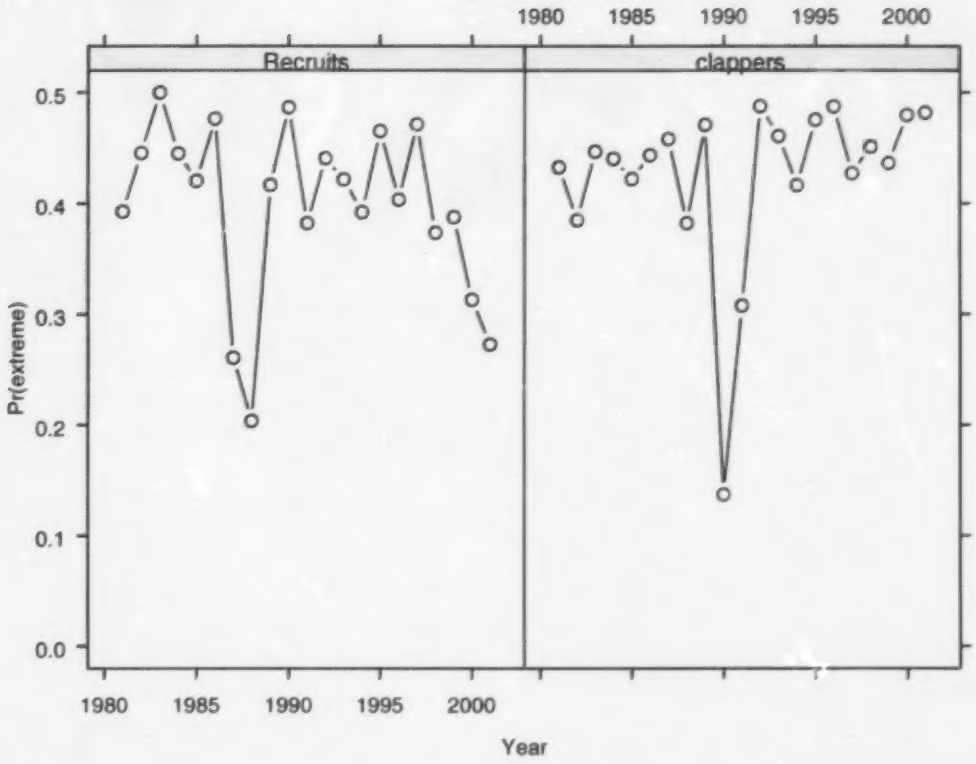

Fig. 24. Probabilities of getting a more extreme observation than obtained for Recruits (left panel) and clappers (right panel).

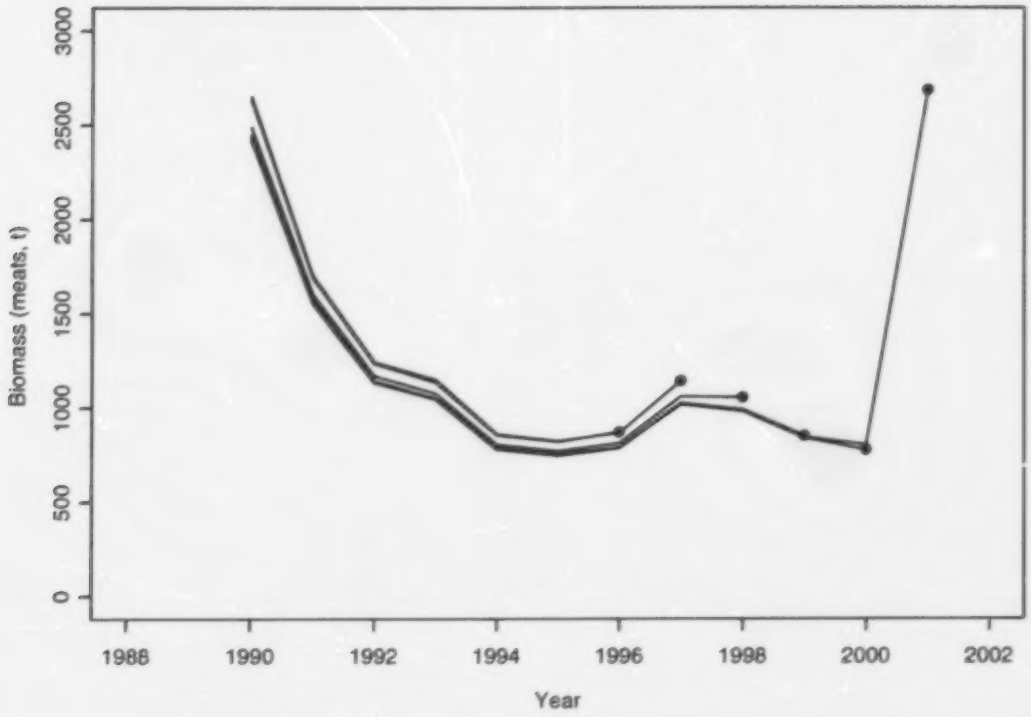

Fig. 25. Retrospective plot for biomass estimates from model fits of the delay difference model using data only up to and including 1996, 1997, 1998, 1999, 2000 and 2001.

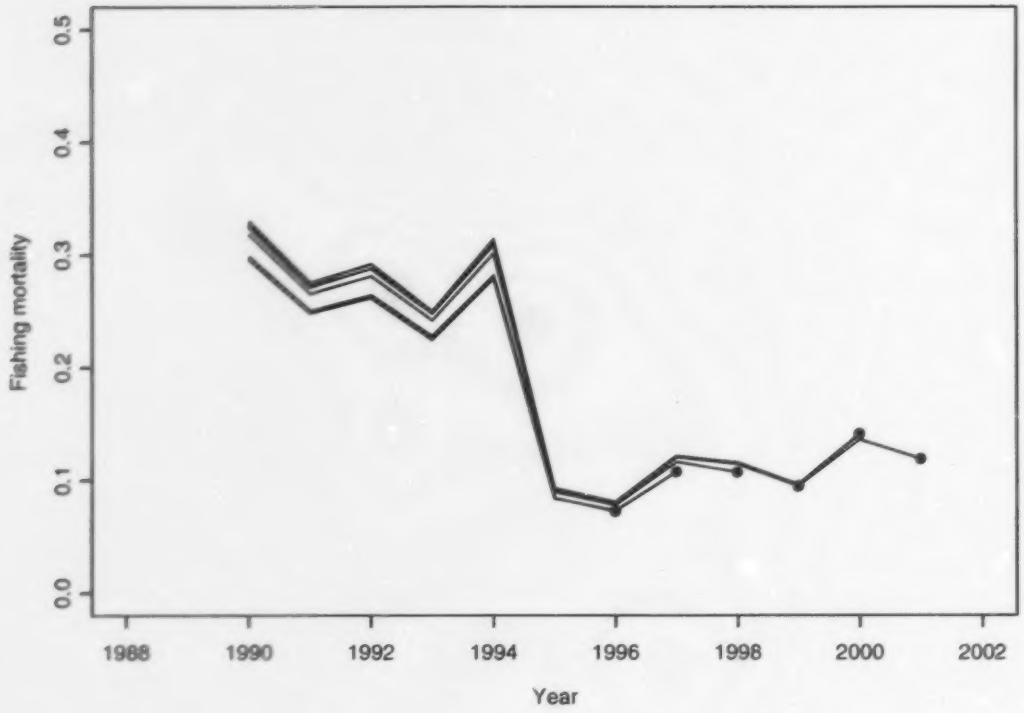

Fig. 26. Retrospective plot for fishing mortality estimates from model fits of the delay difference model using data only up to and including 1996, 1997, 1998, 1999, 2000 and 2001.

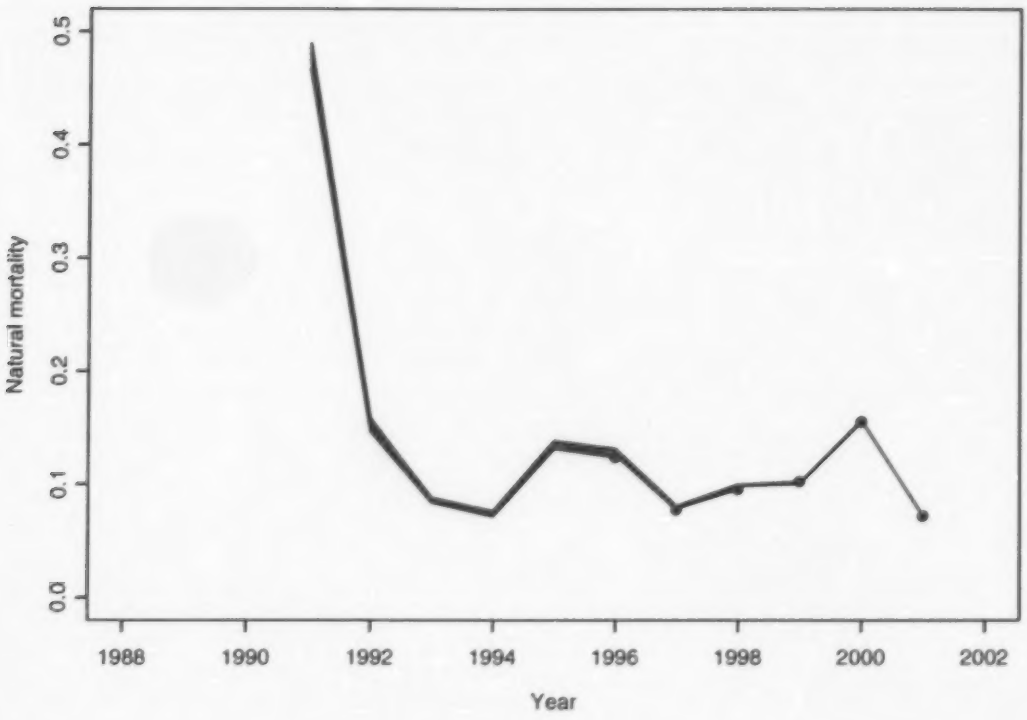

Fig. 27. Retrospective plot for natural mortality estimates from model fits of the delay difference model using data only up to and including 1996, 1997, 1998, 1999, 2000 and 2001.

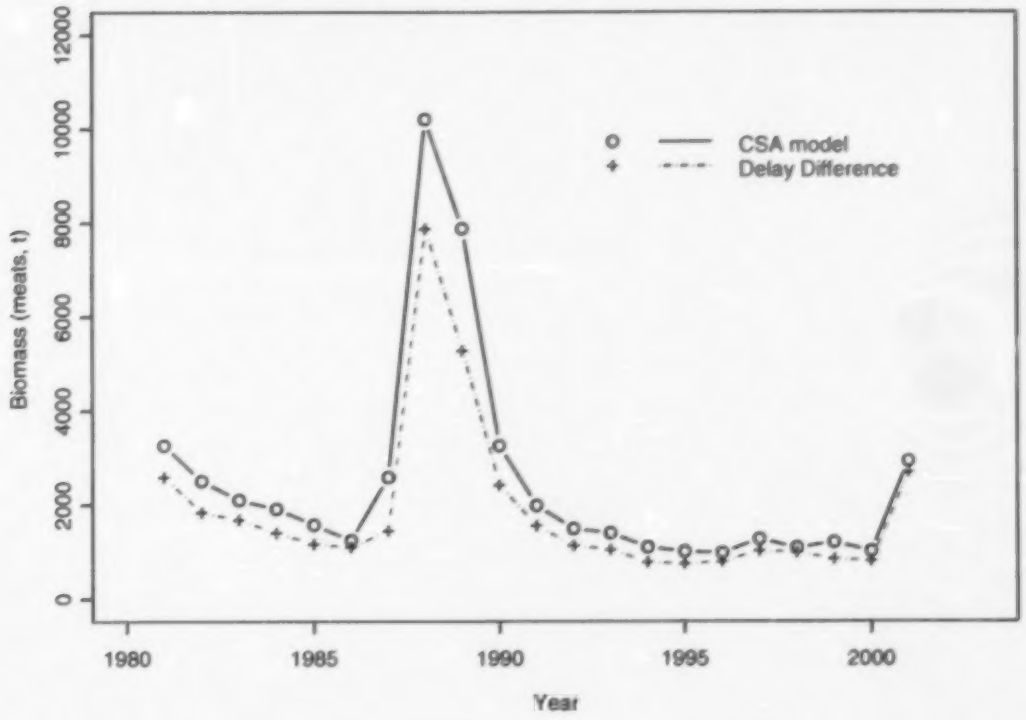

Fig. 28. Predicted biomass for fully-recruited scallops in Scallop Production Area 4. The CSA model results were estimated using the mortality series in Table 17.

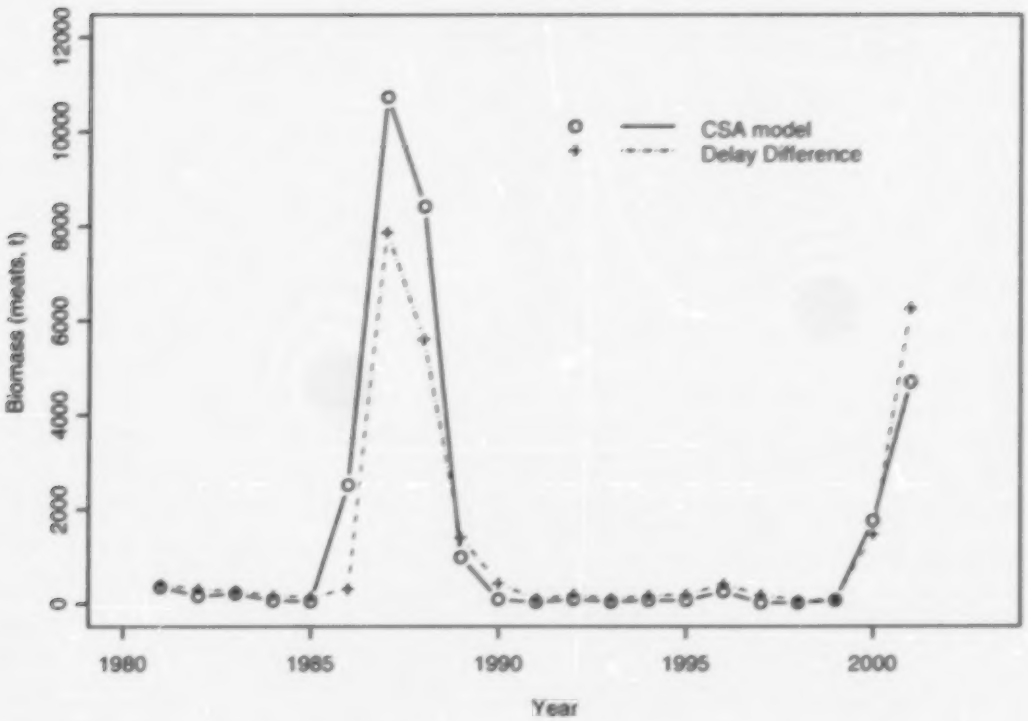

Fig. 29. Predicted biomass for scallop recruits in Scallop Production Area 4. The CSA model results were estimated using the mortality series in Table 17.

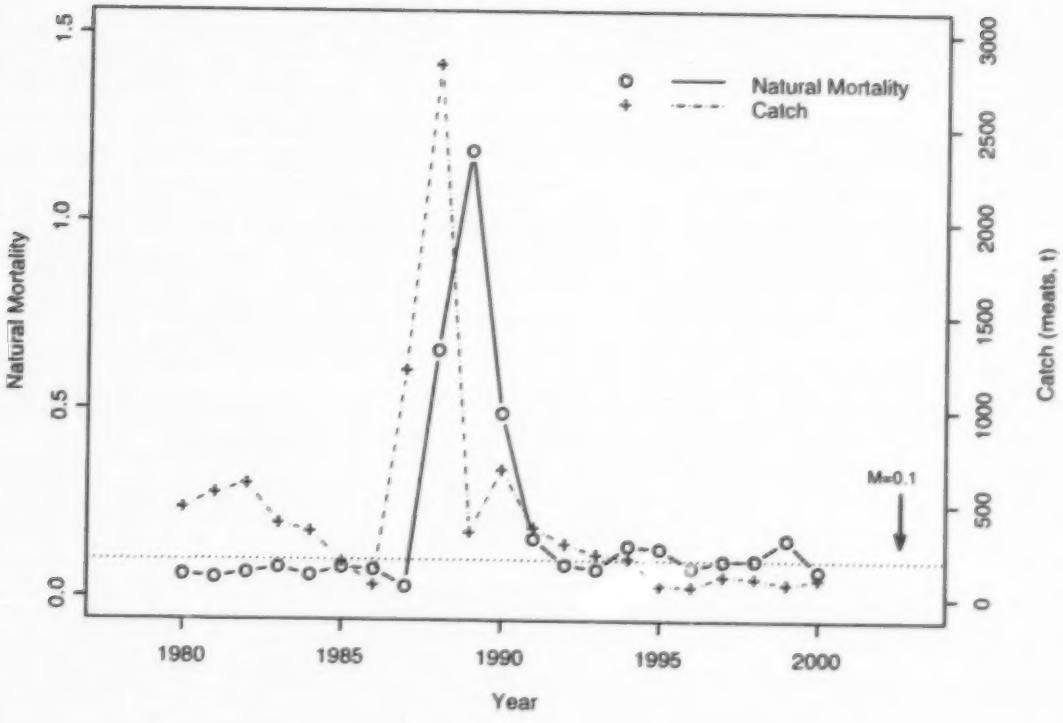

Fig. 30. A comparison of the trends in mortality with those of catch in Scallop Production Area 4.

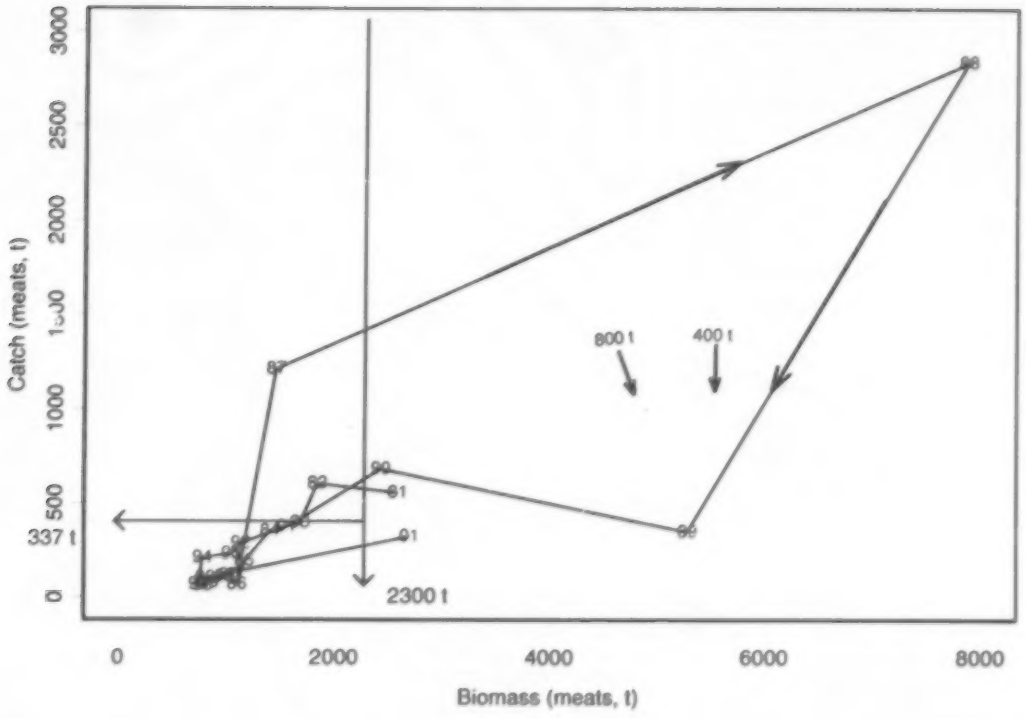

Fig. 31. Phase plot of catch versus estimated biomass of fully recruited biomass (meats, t) for SPA 4 scallops. Points are labelled by year. The vertical line labelled 2300 t refers to the biomass expected when exploiting the stock at $F_{0.1}$ based upon parameters of the population for average recruitment excluding the 1984, 1985 and 1998 yearclasses. The corresponding $F_{0.1}$ catch of 337 t is indicated by the horizontal line. The expected biomass in 2002/2003 for catches of 400 t and 800 t in 2001/2002, respectively, are also labelled for an arbitrary catch of 1000 t in 2002/2003.